Design of Compact Zeroth-Order Resonant Antenna Based on CRLH TL

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This thesis is dedicated to

My parents, grandfather, brother and to all my friends

For their endless love, support and encouragement throughout my career.

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June 2, 2013

Certificate

This is to certify that the thesis entitled ***"Design of Compact Zeroth-Order Resonant Antenna Based on CRLH TL"*** by ***Sumanth Reddy A***, submitted to the National Institute of Technology, Rourkela for the degree of Master of Technology, is a record of an original research work carried out by him in the department of Electronics and Communication Engineering under my supervision. I believe that the thesis fulfils part of the requirements for the award of degree of Master of Technology. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

Prof.S.K.Behera

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Sumanth Reddy A

Abstract

Metamaterial (MTM) Based Antennas are class of antennas inspired by metamaterials to enhance the capability of antenna. Metamaterials have been widely used for microwave circuits and antenna designs due to their unique properties, such as anti-parallel phase and group velocity, and a zero propagation constant at a certain frequency. One of the new applications is the Zeroth-Order Resonant (ZOR) antenna, which is based on Composite Right Left Handed (CRLH) transmission lines (TLs) periodic structures. In addition, ZOR antenna is easy to fabricate and allows design freedoms. Small physical size, low cost, broad bandwidth & good efficiency are desirable features for an integrated antenna. MTM based antennas provide additional degree freedoms & better performance for electromagnetic communication systems.

This thesis presents the design and analysis of Zeroth-order resonant (ZOR) antenna based on Composite Right Left Handed Transmission Line (CRLH -TL). The antenna designed on a ACPW single layer where vias is used. The ZOR phenomenon is employed to reduce the antenna size. The Composite Right Left Handed (CRLH) unit cell on a single layer simplifies the fabrication process. In addition, the ACPW geometry provides high design freedom, so that bandwidth-extended ZOR antenna can be designed. The ZOR characteristic and bandwidth extension are verified by a CST microwave simulator. As an advantage of the proposed method, the size of antenna is reduced, and the resonant frequency of zeroth-order mode is 4.57GHz with radiation efficiency of 75.36%, simulated -10dB fractional bandwidth up to 9.24% and omni-directional peak gain of 1.93 dBi.

***Index terms*—Composite right/left-handed transmission line, coplanar waveguide (CPW), metamaterial, zeroth order resonant (ZOR) antenna.**

Contents

List of Acronymes

ACPW	Asymmetric Coplanar Waveguide
BW	Bandwidth
CMOS	Complementary Metal Oxide Semiconductor
CPW	Coplanar Waveguide
CRLH	Composite Right Left Hand
DNG	Double Negative
EM	Electro-Magnetic
GPS	Global Position System
LH	Left-Handed
LHM	Left-Handed Medium
MEMS	Micro-Electro-Mechanical Systems
MSL	Microstrip-Line
MIMO	Multi-Input Multi-Output
MTM	Metamaterial
NIM	Negative Index Metamaterial
NRI	Negative Refractive Index
PDA	Personal Digital Assistance
RF	Radio Frequency
RH	Right-Handed
RHM	Right-Handed Medium
SRF	Self Resonating Frequency
SRR	Spliy Ring Resonator
TL	Transmission Line

ZOR	Zeroth Order Resonance
VSWR	Voltage Standing Wave Ratio

List of Symbols

$\mathbf{E}$	Electric field intensity vector
$\mathbf{H}$	Magnetic field intensity vector
$\mathbf{S}$	Poynting vector
$\mathbf{k}$	Wave vector
C	Capacitance
C_L	Series capacitance
C_R	Shunt capacitance
G	Shunt conductance
L	Inductance
L_L	Shunt inductance
L_R	Series inductance
R	Resistance
N	Total length of antenna
Q	Quality factor
β	Propagation constant
ϵ	Permittivity
ϵ_0	Permittivity of free space
ϵ_r	Relative permittivity
ϵ_{eff}	Effective permittivity
μ	Permeability
μ_0	Permeability of free space
μ_r	Relative permeability
μ_{eff}	Effective permeability

n	Refractive Index
Γ	Reflection coefficient
$\tan\delta$	Dielectric loss tangent
R_r	Radiation resistance
R_l	Loss or Ohmic resistance
$d\Omega$	Differential solid angle in steradian (sr)
P_{rad}	Radiated power
$U(\theta, \phi)$	Radiation intensity
G_d	Directive gain
D	Directivity
G_P	Power gain
η_r	Radiation efficiency
P_r	Reflected power
V_ϕ	Phase velocity
V_g	Group velocity
f_c	Center frequency
ω	Angular frequency
ω_{se}	Series resonance frequency
ω_{sh}	Shunt resonance frequency
ω_{mp}	Magnetic plasma frequency
W_e	Average electric energy stored in the shunt capacitor C_R
W_m	Average magnetic energy stored in the shunt inductor L_L
c	Speed of light in vacume
λ	Free space wavelength
p	Length of periodic unit cell

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Chapter 1

Introduction

1.1 Introduciton about Antenna

Antenna is defined as an interface between free-space and transmission line that converts Voltage and Current waves to Electro Magnetic waves and vice-versa.

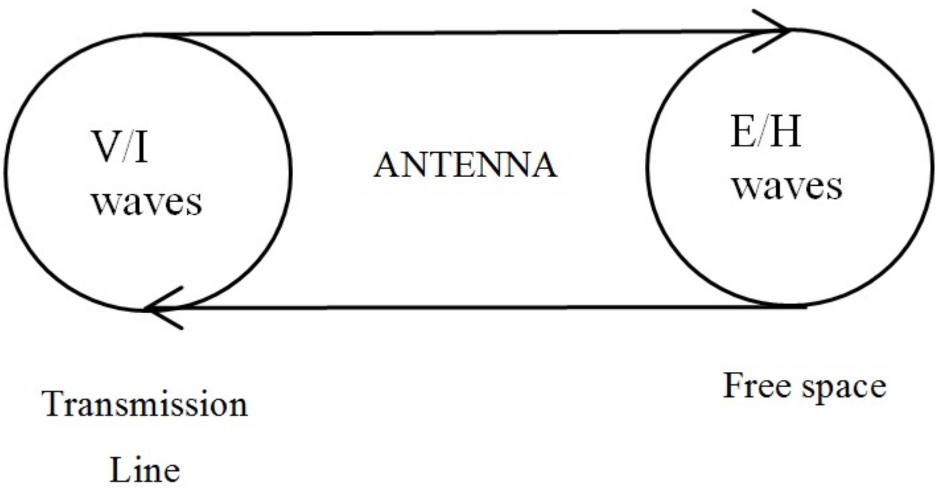


Figure 1.1: Basic Antenna as a Transducer.

The Process of converting V/I waves into E/H is called as Radiation and E/H waves into V/I waves is called as Induction.The radiation or launching of the waves into space is efficiently accomplished with the aid of conducting or dielectric structures called antennas. Theoretically, any structure can radiate EM waves but not all structures can serve as efficient radiation mechanisms.

An antenna may also be viewed as a transducer used in matching the transmission line or waveguide (used in guiding the wave to be launched) to the surrounding medium or vice versa. Fig. 1.2 how an antenna is used to accomplish a match between the line or guide and the medium. The antenna is needed for two main reasons: efficient radiation and matching wave impedances in order to minimize reflection [1]. The antenna uses voltage and current from the transmission line (or the EM fields from the waveguide) to launch an EM wave into the medium. An antenna may be used for either transmitting or receiving EM energy.

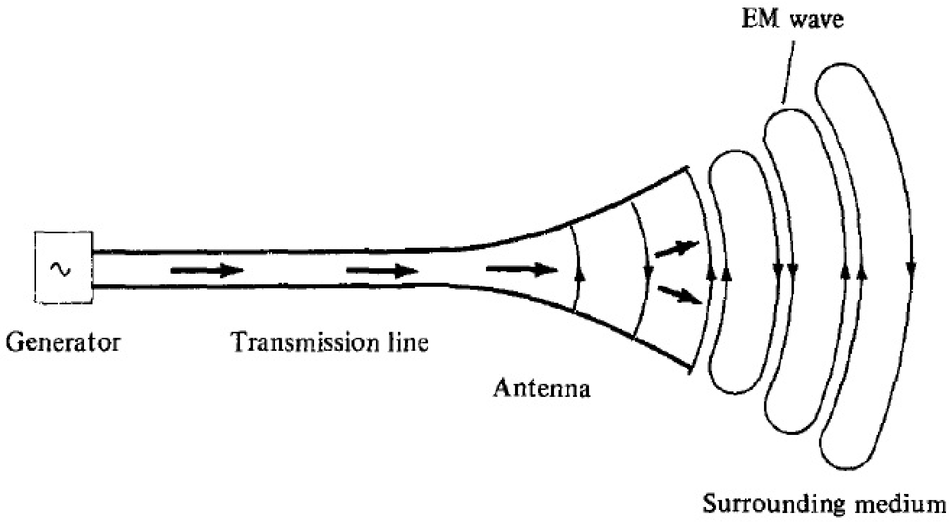


Figure 1.2: Antenna as a matching device between the guiding structure and the surrounding medium.

1.2 Antenna Characteristics

Antennas are characterized by a number of performance measures which a user would be concerned with in selecting or designing an antenna for a particular application. Chief among these relate to the directional characteristics and the resulting gain.The antenna's power gain or simply "gain" also takes into account the antenna's efficiency, and is often the primary figure of merit [1].

1.2.1 Antenna Patterns

An Antenna pattern or Radiation pattern is a three-dimensional plot of its radiation at far field. When the amplitude of a specified component of the **E** field is plotted, it is called the *field pattern* or *voltage pattern.* When the square of the amplitude of **E** is plotted, it is called the *power pattern.*

A three-dimensional plot of an antenna pattern is avoided by plotting separately the normalized $|E_s|$ versus θ for a constant ϕ (this is called an *E-plane pattern or vertical pattern*) and the normalized $|E_s|$ versus ϕ for $\theta = \pi/2$ (called the *H-planepattern or horizontal pattern*) [1]. The normalization of $|E_s|$ is with respect to the maximum value of the so that the maximum value of the normalized $|E_s|$ is unity.

1.2.2 Radiation Intensity

The radiation intensity of an antenna is defined as [1],

$$U(\theta, \phi) = r^2 P_{ave} \tag{1.1}$$

From (1.1), the total average power radiated can be expressed as

$$\begin{aligned} P_{rad} &= \oint_S P_{ave}\ dS = \oint_S P_{ave}\ r^2 \sin\theta\ d\theta\ d\phi \\ &= \oint_S U(\theta, \phi)\ \sin\theta\ d\theta\ d\phi \\ &= \oint_{\phi=0}^{2\pi} \oint_{\theta=0}^{\pi} U(\theta, \phi)\ d\Omega \end{aligned} \tag{1.2}$$

where $d\Omega = \sin\theta\ d\theta\ d\phi$ is the *differential solid angle* in steradian(sr). Hence the radiation intensity $U(\theta, \phi)$ is measured in watts per steradian(W/sr). The average value of $U(\theta, \phi)$ is the total radiated power divided by 4π sr; that is,

$$U_{ave} = \frac{P_{rad}}{4\pi} \tag{1.3}$$

1.2.3 Directive Gain

Besides the antenna patterns described in Section 1.2.1, we are often interested in measurable quantities such as gain and directivity to determine the radiation characteristics of an antenna.

The **directive gain** $G_d(\theta, \phi)$ of an antenna is a measure of the concentration of the radiated power in a particular direction (θ, ϕ).

It may be regarded as the ability of the antenna to direct radiated power in a given direction [1]. It is usually obtained as the ratio of radiation intensity in a given direction (θ, ϕ) to the average radiation intensity, that is

$$G_d(\theta, \phi) = \frac{U(\theta, \phi)}{U_{ave}} = \frac{4\pi\ U(\theta, \phi)}{P_{rad}} \tag{1.4}$$

By substituting (1.1) into (1.4), P_{ave} may be expressed in terms of directive gain as

$$P_{ave} = \frac{G_d}{4\pi\ r^2} P_{rad} \tag{1.5}$$

The directive gain $G_d(\theta, \phi)$ depends on antenna pattern.

The **directivity** D of an antenna is the ratio of the maximum radiation intensity to the average radiation intensity.

Hence, D is the maximum directive gain G_d, max. Thus

$$D = \frac{U_{max}}{U_{ave}} = G_d, max \tag{1.6}$$

or

$$D = \frac{4\pi\ U_{max}}{P_{rad}} \tag{1.7}$$

1.2.4 Power Gain

Power gain or simply *Gain* is a unitless measure that combines an antenna's efficiency η_r antenna and *directivity D*.

Power gain $G_P(\theta, \phi)$ of antenna is defined as [1],

$$G_P(\theta, \phi) = \frac{4\pi\ U(\theta, \phi)}{P_{in}} \tag{1.8}$$

The ratio of the power gain in any specified direction to the directive gain in that direction is referred to as the *radiation efficiency* η_r of the antennas, that is

$$\begin{aligned} \eta_r &= \frac{G_P}{G_d} = \frac{P_{rad}}{P_{in}} \\ \eta_r &= \frac{P_{rad}}{P_{in}} = \frac{R_{rad}}{R_{rad} + R_l} \end{aligned} \tag{1.9}$$

where R_{rad} and R_l are the *radiation resistance* and *loss or ohmic resistance* of the antenna respectively.

1.2.5 Q-factor

The **Q** of an antenna is a measure of the bandwidth of an antenna relative to the center frequency of the bandwidth [2]. A If the antenna operates over a band between f_1 and f_2 with center frequency $f_c = \frac{f_1+f_2}{2}$, then the Q is given by

$$Q = \frac{f_C}{f_2 - f_1} \tag{1.10}$$

Antennas with a high Q are narrowband, antennas with a low Q are wideband. The higher the value of Q, the more sensitive the input impedance is to small changes in frequency.

1.2.6 VSWR

VSWR stands for Voltage Standing Wave Ratio, and is also referred to as Standing Wave Ratio (SWR). For a radio (transmitter or receiver) to deliver power to an antenna, the impedance of the radio and transmission line must be well matched to the antenna's impedance [2]. The parameter VSWR is a measure that numerically describes how well the antenna is impedance matched to the radio or transmission line it is connected to.

VSWR is a function of the reflection coefficient, which describes the power reflected from the antenna. If the reflection coefficient is given by Γ, then the VSWR is defined as

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{1.11}$$

The VSWR is always a real and positive number for antennas. The smaller the VSWR is, the better the antenna is matched to the transmission line and the more power is delivered to the antenna. The minimum VSWR is 1.0. In this case, no power is reflected from the antenna, which is ideal.

And reflected power P_r is given by,

$$P_r\% = (\Gamma)^2 \times 100 \tag{1.12}$$

1.3 Introduction about Metamaterials

Metamaterials (MTMs) are materials typically engineered with novel or artificial structures to produce electromagnetic properties that are unusual or difficult to obtain in nature. Because of their promise to provide engineerable permittivity ϵ, permeability μ and index of refraction, metamaterials have drawn broad interest and have led to possible utilization in many electromagnetic applications from the microwave to optical regime, especially for the radiated-wave devices, for example in antennas designs due to their unique electromagnetic properties, such as anti-parallel phase and group velocities and zero propagation at a certain frequency [3–7].

1.3.1 Literature Review and Methodology

Before proceeding further it is essential to briefly explain the origin of the word Metamaterial and its definition.

There have been large number of definitions for metamaterial, they can be defined as class of"artificial" media, that exhibiting extraordinary electromagnetic properties that can not found in nature once.The word *Metamaterial* is derived word from *Greek*. *Meta* means "*beyond*" or "*higher*". That is Metamaterial can have their electromagnetic properties altered to something beyond the electromagnetic properties of conventional material that found in nature.

Metamaterials refers to an artificial periodic media, for which the periodicity is a fraction of the wavelength of the incident electromagnetic wave [8]. Metamaterial derives its properties from its structure rather than its composition.

About the methodology, all simulations results are carried out by using *Computer Simulation Technology (CST) Microwave(MW) simulator*. CST MICROWAVE STUDIO (CST MWS) is a specialist tool for the 3D EM simulation of high frequency components. CST MWS enables the fast and accurate analysis of high frequency (HF) devices such as antennas, filters, couplers. CST MWS offers powerful solver modules and they are Transient solver, Frequency domain solver, Eigenmode solver and Resonant solver. Transient solver has been used to carry out simulations of the antenna presented in this Report. The Transient Solver of CST MWS is a general purpose 3D EM simulator. Transient Solver also delivers broadband frequency domain results like S-parameters.

1.3.2 Veselago and the Left-Handed Medium (LHM)

In the 1960s, Victor Georgievich Veselago is a Russian physicist proposed the materials with simultaneously negative permittivity ϵ and permeability μ are physically permissible and possess a negative index of refraction. He concluded that such media are allowed by Maxwell' equations and that plane waves propagating inside them could be described by an electric field intensity vector **E**, magnetic field intensity vector **H**, and wavevector **k**. Veselago termed these left-handed media (LHM) because the vectors **E**, **H**, and **k** would form a left-handed triplet instead of a right-handed triplet, as is the case in conventional right-handed media(RHM) [3]. The Two arrangements are shown in Fig.1.3. Moreover, although **E**, **H**, and **k** form a left-handed triplet,**E**, **H**, and the Poynting vector **S** maintain a right-handed relationship. Thus ,in LHM the wavevector **k** is *antiparallel* to the Poynting vector **S**.

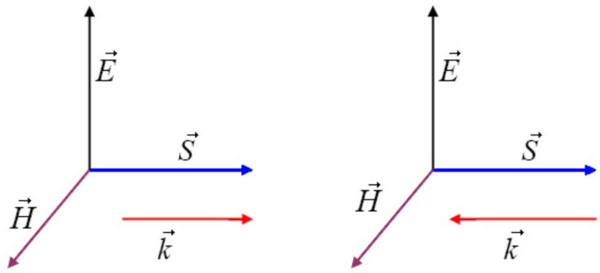


Figure 1.3: Orientation of field quantities **E**, **H**, Poynting vector **S** and the wavevector **k** in right-handed media(RHM) and left-handed media (LHM).

1.4 Background and scope of the thesis

Primary research in metamaterial investigates material with Negative Refractive Index (NRI), which means material will exhibits both permittivity ϵ and permeability μ negative simultaneously, thus leading to Negative Refractive Index.

There are two requirements to achieve a NRI value of refraction. First is to fabricate a material which can produce negative permeability $\mu_{eff} < 0$. Second, negative values for both permeability μ and permittivity ϵ must occur simultaneously over a common range of frequencies.

For obtaining both negative permeability and permittivity simultaneously, some resonance must be present [9]. Resonances are typically observed for "artificial atoms" that are not small compared with the wavelength. By using using some techniques, obtaining small lumped such as capacitors and inductors can shrink the size of the artificial atoms.

Thus, the first Negative Refractive Index or Left Handed Media (LHM) was realized by using a periodic array of thin wires to synthesize negative permittivity and Split Ring Resonator (SRR) to synthesize a negative permeability [10–12]. In later, a another method was developed to realize NRI or Left Handed Media, called Transmission Line method (TL). In this method, Transmission Line is periodically loaded with series capacitors and shunt inductors to obtain NRI. In detail explanation about SRR and TL methods was discussed in section 2.6.

Metamaterial (MTM) technologies can be used to design and develop radio frequency (RF) components and subsystem with performance similar to or exceeding conventional RF structures, at a fraction of existing sizes, for antenna size reduction as much as $\frac{\lambda}{40}$. The techniques can be used to identify suitable structures that are low-cost and easy to manufacture while maintaining high efficiency, gain and compact sizes. one limitation of various MTM antennas and resonators is narrow bandwidth around a resonating frequency in either single-band or multi-band antennas. There have been a number of studies that have investigated how to enhance the bandwidth of Zeroth-Order Resonant (ZOR) antennas [13–16]. In this thesis,we propose a new type of single-layer ZOR antenna that is based on asymmetric coplanar waveguide (ACPW) for a further bandwidth and gain extension. Thus, by using the concept of *Bandwidth Extension of ZOR antenna*, this ZOR antenna extends the bandwidth up to 9.24% and gain 1.93 dBi,and in detail explanation about *Bandwidth Extension of ZOR antenna* also presented in Chapter 4.

1.5 Motivation

The challenges facing next-generation wireless communication systems are multifaceted. On the one hand there is a trend towards the miniaturization of components associated with handheld devices such as laptops, mobile phones, PDA's and GPS's, the space left for the engineers to integrate all the necessary components becomes smaller. When miniaturizing the RF front-end module, the antenna is one of the most difficult components to reduce in size. This is mainly because the conventional resonant antenna size is highly dependent on the operational frequency, thus making the size reduction a challenging task. On the other hand there is a growing demand for faster data transfers, which in turn requires broadband and multi-band components. These two conflicting requirements must be met using low-cost solutions, that simultaneously maintain a high efficiency.

The emergence of a new class of materials called Metamaterial (MTM) have attracted attention since its interesting electromagnetic characteristics have been proposed and experimentally verified. These properties are extensively applied to numerous applications in the microwave field including small antennas. The speciality of the zeroth order mode is the propagation constant in the structure is infinite and the size is independent of resonant frequency [17–20]. As a result the antenna dimension in the resonant direction can be reduced. It has therefore been recognized by many researchers in the field that several important design constraints imposed by next-generation wireless systems can be addressed through the use of metamaterial technology.

1.6 Objective of Thesis

Since the Zeroth Order Resonator (ZOR) antenna suffers from low bandwidth around the resonating frequency, the main objective of present research work is to propose efficient technique for extending bandwidth and increasing gain while maintaining high efficiency. Recently many researchers have attempted to solve the bandwidth problem of ZOR antennas [13–15, 21, 22]. To accomplish this,

- A matamaterial ring antenna was reported in [13]. This antenna was implemented on a multi-layer structure in which a thick substrate with low permittivity is used, and its bandwidth is increased up to 6.8%.
- Alternatively,the bandwidth of the ZOR antenna is increased by a strip matching ground [14]. It is also built on a multiple substrate where a thin substrate with high permittivity is stacked on a thick substrate with low permittivity. In this method, fractional bandwidth of antennas is increased up to 8%.
- The other method is to have two resonant frequencies close to each other [15]. Such antennas consists of two resonators whose frequencies are slightly different. In this method, bandwidth is increased up to 3.1%.
- By realizing ZOR antenna using CPW technology, will allow design freedom for the shunt parameters in the equivalent circuit mode. Thus, bandwidth of ZOR antenna is extended up to 6.8% by realizing high shunt inductance and small shunt capacitance using CPW technology [16].

In this thesis, novel compact Asymmetric Coplanar Waveguide ZOR antenna is designed based on CRLH-TL. In this method Transmission line is loaded periodically with capacitors and inductors. According to bandwidth extension of ZOR antenna theory, bandwidth of the open-ended ZOR antenna depends on the shunt elements of CRLH-TL equivalent circuit model. Therefore, we can increase the bandwidth by altering the shunt element values. This ZOR antenna extends the bandwidth up to 9.24% and peak gain of 1.93 dBi while keeping good radiation efficiency.

1.6.1 Structure and chapter wise contribution of the thesis

Chapter-1
The basic understanding about antenna, important antenna characteristics and brief explanation about Metamaterials are introduced in this chapter. The motivation behind the research in metamaterials also outlined. The summary of framework of the research and contribution are also included in this chapter.

Chapter-2
In this chapter about negative index metamaterial is explained. The response of material to EM wave, which is necessary to understand about metamaterial is also presented. Important background theory about negative permeability , permittivity and how to achieve these in practically is also explained. Finally, methods to realize NRI or LH media is presented.

Chapter-3
In this chapter briefly explained about various type of microstrip inductors and microstrip capacitor, and also shown the these microwave components diagrammatically. CRLH TL theory, its equivalent circuit and important relations associated with the theory is presented. Finally, about Zeroth Order Resonance and its effect on making ZOR antenna is independent of physical length and application of Metamaterial Transmission Line is discussed.

Chapter-4
In this chapter we proposed a bandwidth extension technique for open ended ZOR antenna and showed the relation between bandwidth of the antenna and the circuit elements. Proposed ACPW ZOR antenna based on CRLH TL is shown with physical dimensions and prototype of fabricated antenna is also presented. Finally this chapter concluded with simulation results of reflection coefficient, radiation patterns on the E-plane and H-plane of the antenna at resonance frequency and parametric study of antenna for different parameter variations.

Chapter-5
In this chapter, the conclusion of the whole thesis is presented and future research problems are outlined for further investigation in the same or related topics.

1.7 Conclusion

This chapter provides a brief introduction about antenna, its important characteristic and about metamaterials. This chapter also outlined the brief explanation about how to realize Left Handed media or Negative Refractive Index and also unique properties of metamaterials.

Chapter 2

Negative Refractive Index (NRI) Metamaterials

Metamaterial Based Antennas are class of antennas inspired by metamaterials to enhance the capability of antenna. The primary research in metamaterials investigates materials with negative refractive index. When a negative index of refraction occurs,propagation of the electromagnetic (EM) wave will get reversed. Also, reversing the EM wave in material, could result in minimizing losses that would normally occur. The reverse of the EM wave is characterized by an anti-parallel phase and group velocities v_ϕ and v_g respectively, is also an indicator of negative index of refraction. This is the unique property of metamaterial compared to the materials which occur naturally.

2.1 Negative Index Metamaterials

In negative index metamaterials, both permeability μ and permittivity ϵ are negative simultaneously, thus its leads to a negative index of refraction or negative refractive index. Hence, because of the double negative parameters these are also known as Double Negative Metamaterials or double negative materials (DNG) [23]. Other terminologies for NRI are “left-handed media”, “media with a negative index of refraction” [24], and “backward-wave media”, since the the wavevector $\mathbf{k}$ is *antiparallel* to the Poynting vector $\mathbf{S}$.

In conventional materials, both permeability μ and permitivity ϵ are positive this results in propagation in the forward direction. If both μ and ϵ are negative, a backward wave is produced. If ϵ and μ have different polarities, then this does not result in wave propagation called *Evanescent mode*.

As mentioned before, Electric permittivity and magnetic permeability are the parameters determine the electric and magnetic response to electromagnetic radiation. The following Fig 2.1 show the possible wave propagations in materials with different values of electrical permittivity μ and magnetic permeability ϵ.

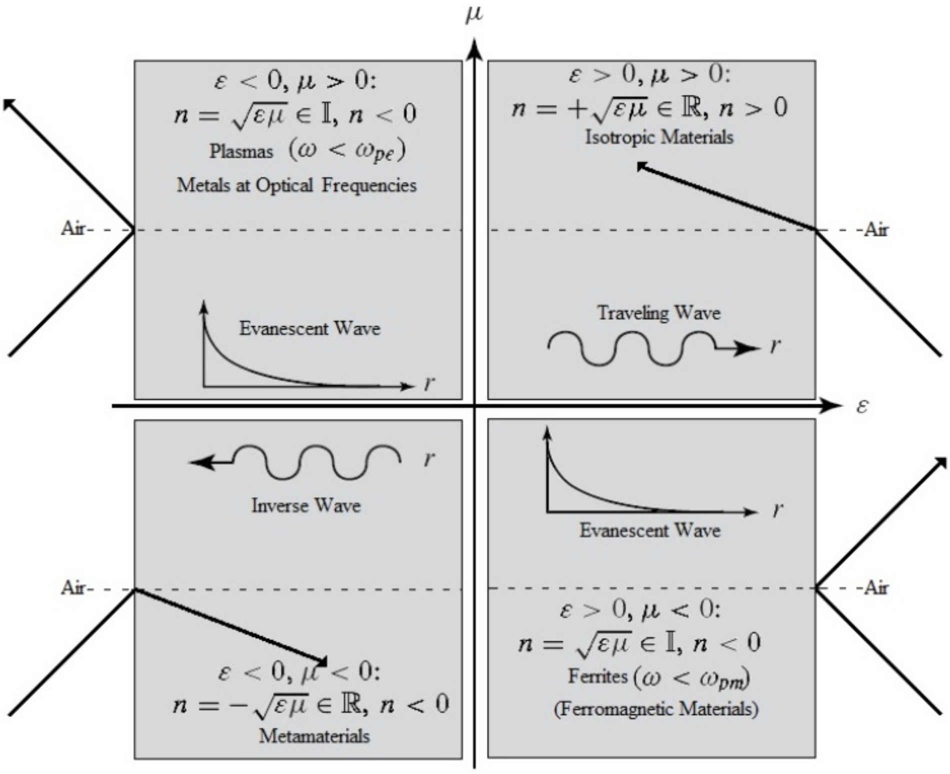


Figure 2.1: Possible wave propagations in materials with different values of electrical permittivity μ and magnetic permeability ϵ.

2.2 Response of material to EM wave

It is necessary to understand material response to EM waves in order to understand the concept of metamaterial. EM response in homogeneous materials is predominantly governed by two parameters called electrical permittivity ϵ and magnetic permeability μ. The response of a material to the electric component of EM wave is described by ϵ, and similarly response of a material to the magnetic component of EM wave is described by μ at frequency ω. Both of these parameters are typically frequency-dependent complex quantities. Thus, these both parameters will completely describe the response of an isotropic material to EM radiation at given frequency [25] is given by

$$\begin{aligned} \epsilon(\omega) &= \epsilon_1(\omega) + i\epsilon_2(\omega) \\ \mu(\omega) &= \mu_1(\omega) + i\mu_2(\omega) \end{aligned} \tag{2.1}$$

Index of refraction or *Refractive index n*, which is defined as,

$$n(\omega)^2 = \epsilon(\omega) \times \mu(\omega) \tag{2.2}$$

The speed of an EM wave as it propagates within a material is measured by *Index of refraction* or *Refractive index n*. In addition, The refractive index also provides a measure of the deflection of a beam of light as it crosses the interface between two materials having different values for their refractive indices.
According to *Snell's law*, the quantitative measure of bending is give by,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{2.3}$$

where n_1 and n_2 are the *refractive index* of first and second media respectively,and θ_1 and θ_2 are the angles the EM wave makes with the surface normal of each media.

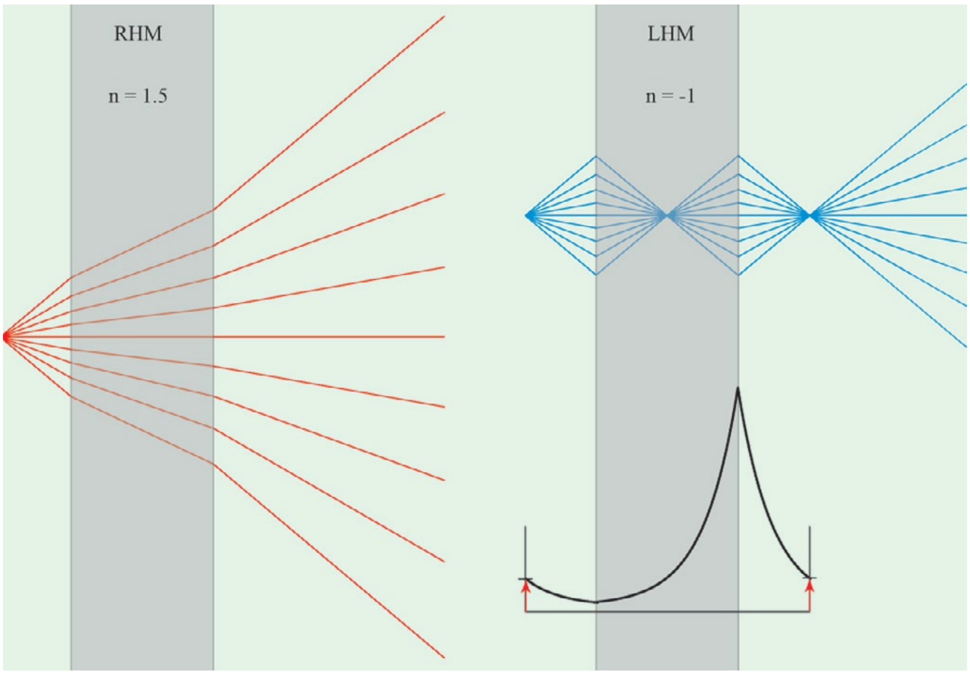


Figure 2.2: EM wave propagation inside material for positive and negative value of n.

In Fig 2.2, the simple ray tracing diagram for rays emanating from a in free space, incident on a slab with positive index of refraction is shown. On reaching the surface of the slab, the rays emanating from the source bend at the interface between free space and the glass with an angle as determined by (2.3). On the right, a flat slab of Negative Index material is shown. In this case the rays refract at the interface, again governed by Snell's law, but this time with n= -1. Also shown on the bottom right is the evanescent component of this point source.

2.3 Materials with Negative Permittivity

It is well known that plasmas are described by a permittivity function that becomes negative below a plasma frequency ω_P, causing the propagation constant in the plasma to become imaginary. In this region, electromagnetic waves incident on the plasma suffer reactive attenuation and are reflected. Thus, the plasma frequency bears a resemblance to the modal cutoff frequencies of particular electromagnetic waveguides, below which the waveguide environment can be perceived as an inductively loaded free space, as observed in 1954 by R. N. Bracewell [26]. The idea of modelling plasmas using artificial dielectrics was examined as early as 1962 by Walter Rotman [27]. Rotman considered Kock's artificial dielectrics, and he employed the well-know theory for the analysis of periodic microwave networks to determine their dispersion characteristics. His analysis, however, could not explicitly consider the permittivity of the media and instead, was limited to the consideration of their index of refraction. Rotman noted that an isotropic electrical plasma could be modelled by a medium with an index of refraction below unity, provided that its permeability was near that of free space. The idea of a negative permittivity was implicit in any such works, but it was not until nearly a quarter-century later, when Rotman's rodded dielectric was rediscovered, that it was made clear exactly how a wire medium resembled a plasma.

Although the permittivity is negative at frequencies below the plasma frequency, the approach toward absorptive resonances at lower frequencies increases the dissipation, hence the complex nature of ϵ. Thus, to observe a negative permittivity with low absorption at microwave frequencies, it would be necessary to somehow depress the plasma frequency of the metal. This problem was addressed by Pendry *et al.* [28] and simultaneously by Sievenpiper *et al.* [29], who proposed the familiar structure of Rotman consisting of a mesh of very thin conducting wires arranged in a periodic lattice. Thus. an array of thin metallic wires, by virtue of its macroscopic plasma-like behaviour, produces an effectively negative permittivity at microwave frequencies. The following Fig 2.3 shows the split-ring resonator (SRR) of Pendry *et al.* in planar form. At optical frequencies silver, gold, and aluminium displays a negative ϵ_r at optical frequencies.

2.4 Material with Negative Permeability

It is important to note that in the effort to synthesize a negative effective permittivity, Rotman and Pendry relied on the analogies their structures shared with the simplified electrodynamics of natural substances. Indeed, as acknowledged by Veselago himself, it is a much more difficult task to synthesize an isotropic negative permeability ($\mu < 0$).

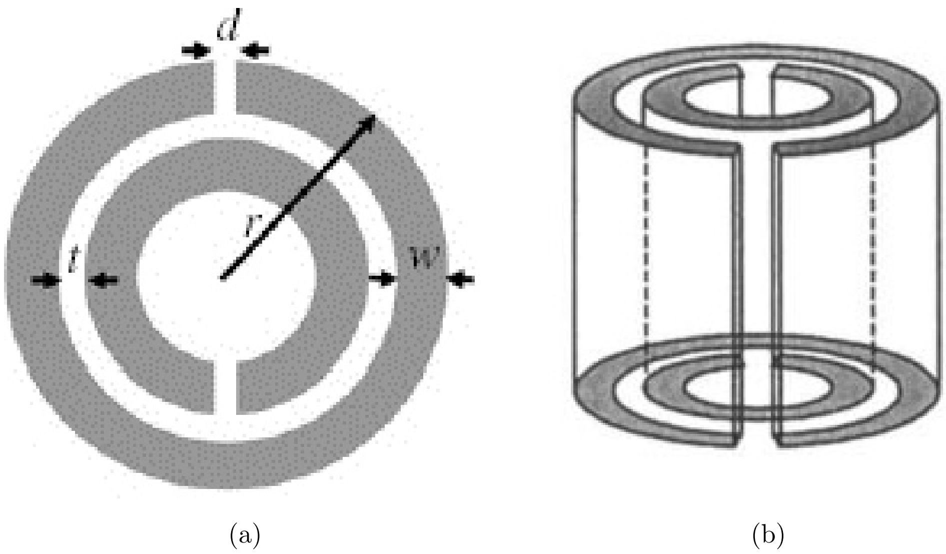


Figure 2.3: The split-ring resonator (SRR) of Pendry *et al.* [30] in planar and cylindrical form.

In 1999, Pendry *et al.* [30] claimed to have developed microstuctured artificial material exhibiting strange magnetic properties. The work first developed expressions for the magnetic properties of materials resembling the wire mesh, in which the fields and currents are oriented along the wire axis. This work concluded that such materials are strictly diamagnetic and that the permeability approaches the free-space value as the radius of the wires is decreased, a response which may be expected of simple artificial dielectrics [31]. However, by giving the cylinders an internal electromagnetic structure resembling a parallel-plate capacitor wrapped around a central axis, Pendry *et al.* noticed a very different behaviour. The resulting split-ring resonator (SRR), shown in Fig.2.3, exhibits strong electric fields, supported by a very large capacitance, between the rings. Even though the currents cannot traverse the gaps, the application of magnetic fields oriented normal to the plane of the rings induces simultaneous currents in both rings. This synthesized capacitance, along with the natural inductance of the cylindrical structure, results in a resonant response characterized by an effective relative permeability of the form, given below.

$$\mu_{eff} = 1 - \frac{\frac{\pi r^2}{a^2}}{1 - j\frac{2l\rho}{wr\mu_0} - \frac{3l}{\pi^2\mu_0\omega^2 Cr^3}} \tag{2.4}$$

where r represents the radius of the SRR, a is the lattice spacing of SRRs lying in the same plane, l is the spacing between planes, p represents the resistive losses of the metal sheets, and C is the sheet capacitance between the two sheets. It is clear from the resonant form of μ_{eff} that an artificial medium composed of SRR arrays would exhibit an effective permeability that attains large values near the resonance.

From (2.4), resonance frequency is given by

$$\omega_0 = \sqrt{\frac{3l}{\pi^2 \mu_0 C r^3}} \tag{2.5}$$

when $\sigma \rightarrow 0$,the permeability expression can become negative if the second term of 2.4 is greater than one. This occurs at an effective magnetic plasma frequency ω_{mp}, given by

$$\omega_{mp} = \sqrt{\frac{3l}{\pi^2 \mu_0 C r^3 (1 - \frac{\pi r^2}{a^2})}} \tag{2.6}$$

The quantity $\frac{\pi r^2}{a^2}$, which is denoted by $\boldsymbol{F}$, is the fractional area occupied by the rings. When embedded in air, arrays of SRRs appear to exhibit a stopband in the frequency region enclosed by ω_0 and ω_{mp}, suggesting that the permeability is negative in this region. Thus, comprising purely non-magnetic materials, the SRR array of Pendry *et al.* had successfully simulated an artificial magnetic plasma, for which the effective permeability assumes negative values at microwave frequencies. Resonant ferromagnet system exhibits negative permeability ($\mu < 0$) at resonance.

2.5 Mathematical explanation for NRI

The electrical permittivity $\epsilon = \epsilon_r \epsilon_0$ and the magnetic permeability $\mu = \mu_r \mu_0$ are the general parameters of a material which supports electromagnetic waves. By using these parameters, we can relate speed of a wave in the medium v_ϕ to the speed of the light c through the index of refraction as follows,

$$n = \frac{c}{v_\phi} \tag{2.7}$$

Depending on sign of phase velocity, the index of refraction in (2.7) can be either positive or negative. By substituting ϵ and μ into (2.7), expression for index of refraction can be given as follows,

$$n = \sqrt{\epsilon_r \mu_r} \tag{2.8}$$

By considering simultaneously both the values of ϵ and μ are negative, further index of refraction can related as,

$$n = \sqrt{\epsilon_r \mu_r} = (e^{-j\pi} \times e^{-j\pi})^{\frac{1}{2}} = e^{-j\frac{\pi}{2}} \times e^{-j\frac{\pi}{2}} = e^{-j\pi} = -1 \tag{2.9}$$

From (2.9) it is clear that negative index of refraction can be achieved when both ϵ and μ occur simultaneously negative.

2.6 Realization of NRI

It has been known for some time that arrays of thin metallic wires, by virtue of their collective plasma-like behaviour can produce an effectively negative dielectric permittivity, it was not clear as to how to produce a simultaneously negative permeability. The recent development of the split-ring resonator (SRR) by Pendry *et al.* was successful in this effort. Subsequently, three-dimensional (3-D) electromagnetic artificial dielectrics, consisting of an array of resonant cells, each comprised of thin wire strips and split ring-resonators, were developed to synthesize the simultaneously negative permittivity and permeability required to produce a negative refractive index.

2.6.1 Split Ring Resonator

A famous microwave structure for obtaining NRI is the split-ring resonator. It consist of two metallic micro strip rings with a slit as shown in Fig. 2.3. They may have very different shape, Circular and square rings are most simple. Even these simple configurations have several parameters that need to be tuned in such a way that the desired NIM property is observed at some frequency. The split ring resonator may be considered as a small antenna that is responsible for the negative permittivity. Veselago recognized that plasmas could be used to obtain a negative permittivity, and he speculated that some kind of a magnetic plasma (not available naturally) would be needed to obtain a negative permeability. The solution to the problem of realizing such an Left Handed (LH) or NRI medium was solved three decades later by Shelby, Smith, and Schultz, inspired by the work of John Pendry. The structure that was an array of strip wires to synthesize a negative permittivity and a structure called the “split-ring resonator”, a capacitively loaded loop, to synthesize a negative permeability, as shown in Fig.2.4.

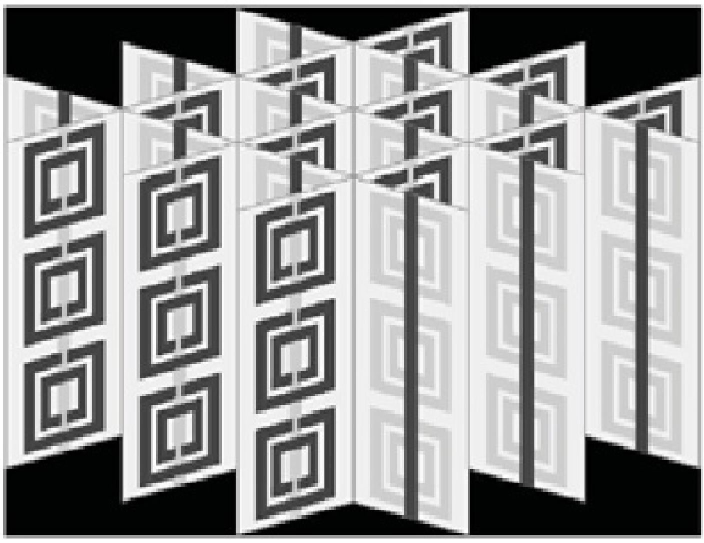
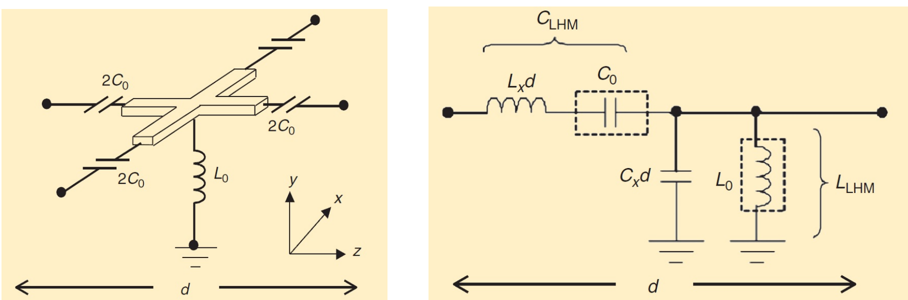


Figure 2.4: The structure used by Shelby, Smith, and Schultz *et al.* [32] to verify negative refraction.

2.6.2 Transmission Line method to realize NRI

Negative Index Metamaterials made of split ring resonators and wire antennas may be considered as arrays of resonating antenna structures. An alternative method for realizing LH metamaterials consists of loading a host transmission-line (TL) medium with reactive elements [4,33,34]. For example, for synthesizing an LH metamaterial in two dimensions, a host microstrip line network can be loaded periodically with series capacitors and shunt inductors, as shown in Fig.2.5. Such loaded lines support backward waves.



(a) (b)

Figure 2.5: (a)TL is loaded periodically with series capacitors and shunt inductors. (b) Equivalent TL when $\beta d \to 0$.

An experimental prototype of large periodically loaded transmission line is show in Fig.2.6. The prototype was developed by Ashwin K. Iyer, Peter C. Kremer and George V. Eleftheriades [35] at University of Toronto,Canada. The experimental prototype measures approximately $105mm \times 305mm \times 1.5mm$ and is shown in Fig.2.6. In the inset, magnification of a single NRI unit cell is shown, consisting of a microstrip grid loaded with surface-mounted capacitors (in series) and an inductor embedded into the substrate (in shunt) at the central node, similar to the schematic presented in Fig.2.5.

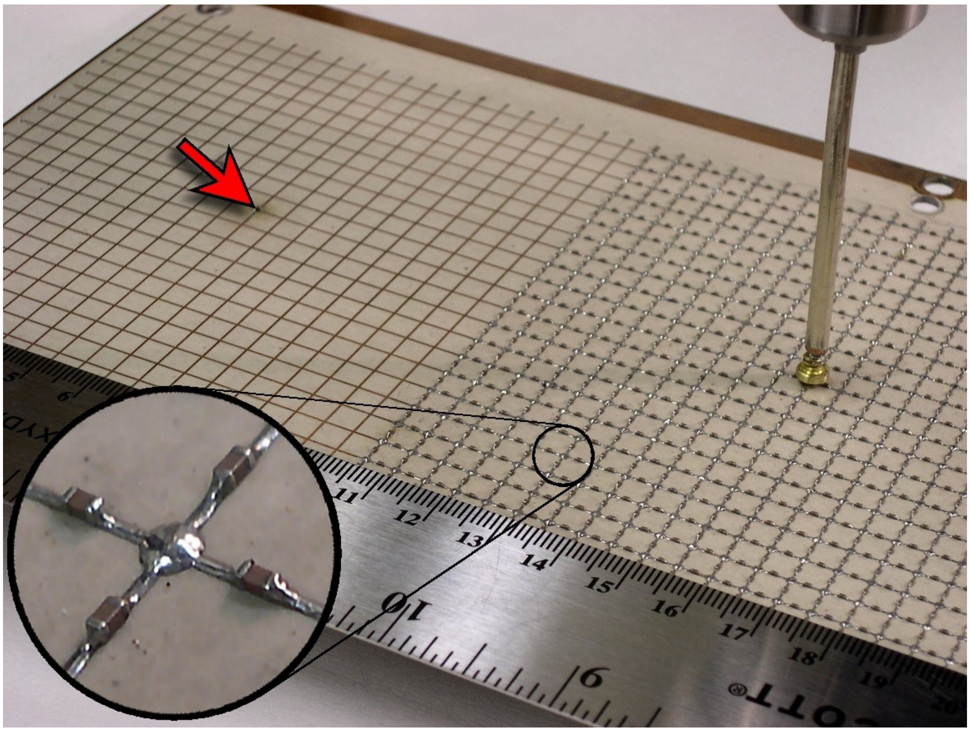


Figure 2.6: Experimental prototype of large periodically TL developed by Ashwin K. Iyer, Peter C. Kremer and George V. Eleftheriades [35] at University of Toronto,Canada.

2.7 Conclusion

Thus, after thirty-five years dedicated research veselago's idea have been verified experimentally using electromagnetic artificial dielectrics. Such NRI or LH media was first realized by using periodic array of thin wires to synthesize a negative permittivity and a famous microwave structure for obtaining NRI is the split-ring resonator to synthesize a negative permeability. An alternative method also presented to realize NRI called Transmission Line method, a host TL periodically loaded with series capacitors and shunt inductors.

Chapter 3

Characterization of CRLH-Transmission Line

As explained in the Section 1.3.2 Veselago and the left handed medium, metamaterial is an artificial structure. When designed with a structural average unit cell size, let say p as shown in Fig. 3.3 much smaller than the wavelength of the electromagnetic energy guided by the metamaterial, then the metamaterial can behave like a homogeneous medium to the guided electromagnetic energy. Different from RH material, a metamaterial can exhibit a negative refractive index where the phase velocity is opposite to the direction of the signal energy propagation [3] where the relative directions of the ($\mathbf{E}$, $\mathbf{H}$, $\mathbf{k}$) vector fields, where $\mathbf{E}$ is the electric field, $\mathbf{H}$ is the magnetic field, and $\mathbf{k}$ is the wave vector follow the left handed rule.

In general conventional material, propagation of electromagnetic waves in most materials obeys the right handed rule for the ($\mathbf{E}$, $\mathbf{H}$, $\mathbf{k}$) vector fields. The phase velocity direction is the same as the direction of the signal energy propagation (group velocity) and the refractive index is a positive number. Such material are called "Right Handed (RH)" materials. Most natural materials are RH materials. Artificial materials can also be RH materials.

In the following Section 3.1, different type of possible circuit elements to develop the effect of CRLH is discussed, and brief explanation about each lumped microwave components is discussed.

3.1 Lumped Microwave Components

Lumped components have the advantage of small size, low cost, and wide-band characteristics, but have lower $Q$and lower power handling than distributed elements. To function well as a lumped element at microwave frequencies, the length of the equivalent inductor and capacitor elements should not be longer than 12% of a wavelength λ, or they will begin to lose their lumped equivalence effect.

3.1.1 Microstrip Inductors

- The inductance value of a Microstrip inductor is determined from the total length, the number of turns, spacing, and line width.
- Narrow tracks are more inductive but carry less current, so there is a trade-off between them.
- Spiral track inductors have more inductance because the magnetic fields from each turn of the spiral add up, creating a larger field through the middle of the spiral and mutual inductance between all the turns.
- The high-impedance, straight-line or wire inductor is the simplest form of an inductor, used for low inductance values (typically up to 3 nH), while the spiral inductor (circular or rectangular) can provide higher inductance values, typically up to 10 nH.
- The inductance of an isolated (no ground plane), flat, ribbon inductor (or Strip Inductor) is given approximately by,

$$L(nH/mm) = 0.2\left\{\ln\left[\frac{l}{w+t}\right] + 1.93 + \frac{0.2235(w+t)}{l}\right\} \tag{3.1}$$

  where w is width, t is metal thickness, and l is length.

- The inductance of a strip inductor is decreased by the presence of a ground plane. The effective inductance of a strip inductor using a ground plane is given by,

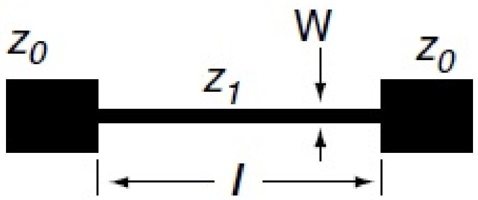
$$L_{eff} = \left[0.570 - 0.145\ \ln\left(\frac{w}{h}\right)\right] \times L \tag{3.2}$$

  where h is the substrate height.

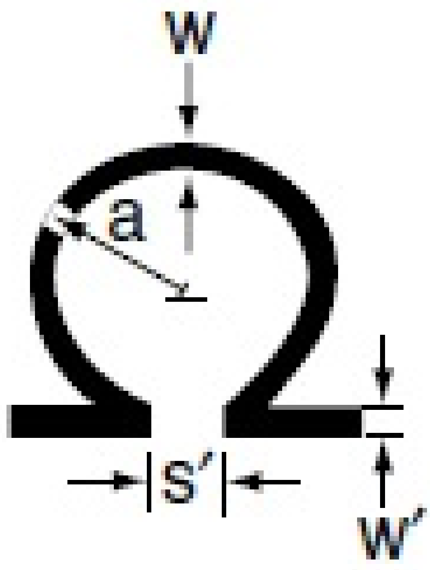
Many different types of Spiral Inductors are used in Microstrip development, such as circular, octagonal spirals and single-turn spiral. . . etc.

Meander-line Inductor:

- The **Meander-line Inductor** is used to reduce the area occupied by the element.
- In the meander inductor, adjacent conductors have equal and opposite current flows, which reduce the total inductance.
- Meander-line inductors have the advantage of lower eddy current resistance, but the disadvantage is lower inductance and lower SRF (self-resonant frequency) than spiral inductors.

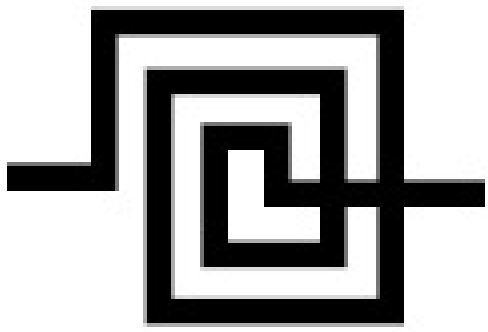


(a) Wire Inductor



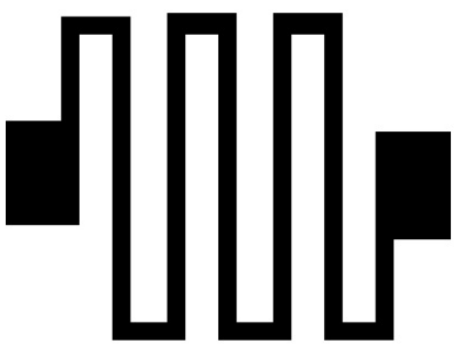
(b) Single turn

(c) Circular spiral



(d) Square spiral

(e) Octagonal spiral



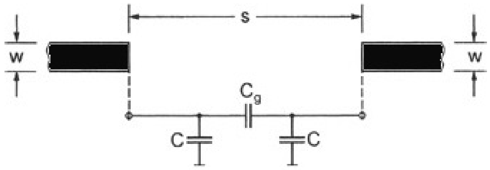
(f) Meander line

Figure 3.1: Different type of microstrip inductors

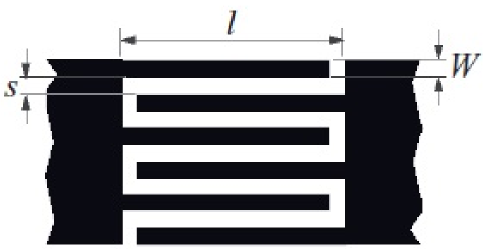
3.1.2 Microstrip Capcitors

- Capacitors are lumped circuit elements that store energy by virtue.
- The **Gap Capacitor** can be described as two coupled open-ended Microstrip lines. The capacitance C refers to the open-end capacitance and the series gap capacitance C_g describes the electrical coupling.
- The **Interdigital Capacitor** relies on the strip-to-strip capacitance of parallel conducting fingers on a substrate and its suitable for applications where low values of capacitance are required.
- The finger width **W** must equal the space **s** to achieve maximum capacitance density, and the substrate thickness**h** should be much larger than the finger width.
- Fundamental **Parallel-Plate Capacitors** consisting of a pair of parallel planar metallic surfaces separated by a dielectric are available in chip forms as discrete components.
- The **Metal-Insulator-Metal (MIM)** Capacitor, constructed by using a thin layer of a low-loss dielectric between two metal plates, is used to achieve higher values in the order of tens of pF in small areas.
  The MIM capacitance is given by the classical expression from electrostatics

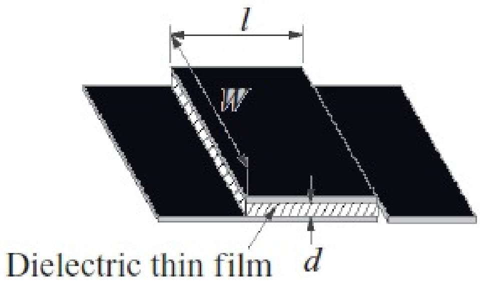
$$C = \frac{0.0885\epsilon W l}{h}(pF) \tag{3.3}$$



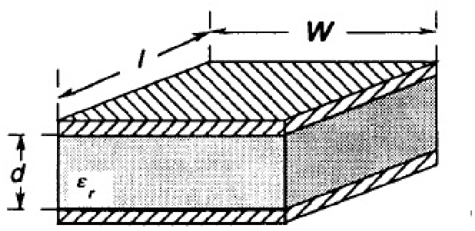
(a) Gap capcitor and Equivalency



(b) Interdigital Capacitor



(c) MIM Capacitor



(d) Parallel Plate Capacitor

Figure 3.2: Different type of microstrip capacitors

3.2 CRLH TL Theory

Metamateriasl are mixture of LH metamaterials and RH materials thus are called Composite Right Left Handed. A CRLH metamaterial can behave like a LH metamaterial at low frequencies and a RH material at high frequencies.

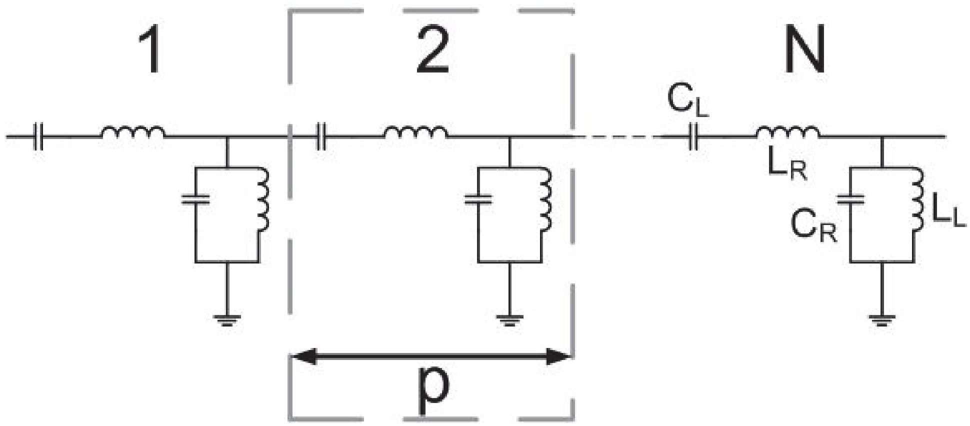


Figure 3.3: Equivalent circuit model for CRLH-TL

The above Fig. 3.3 shows the equivalent circuit model of N unit cell CRLH-TL.From the equivalent circuit above, it is clearly that the length of unit cell p, and the total length of the antenna is N times the length of unit cell p, L=N×p. Only the phase shift satisfy $\beta L = n\pi$, do the antenna resonant, and the resonant index,n can be positive integer, zero, even negative integer.

From Fig.3.3 the cascaded series inductance L_R and shunt capacitance C_R are of right handed transmission line, and cascaded shunt inductance L_L and series capacitance C_L are of left handed transmission line. The shunt capacitance C_R mostly come from ground which indicates that this capacitance can not be ignored [36]. So a purely left handed metamaterials transmission line (consist of cascade series capacitance C_L and shunt inductance L_L) based on microstrip is unrealistic, the parasitic right handed transmission line effects should also be taken into account.

In general CRLH TL is designed in a periodic configuration consists of capacitors and inductors, by cascading N unit cells. The immitances of a lossy CRLH TL are give by

$$Z'_{series} = R + j\left(\omega L_R - \frac{1}{\omega C_L}\right) \tag{3.4}$$

$$Y'_{series} = G + j\left(\omega C_R - \frac{1}{\omega L_L}\right) \tag{3.5}$$

where R and G are the series resistance and shunt conductance of the lossy CRLH

TL, respectively [37,38]. The series and shunt resonant frequencies are given by

$$\omega_{se} = \frac{1}{\sqrt{L_R C_L}} \quad rad/s \tag{3.6}$$

$$\omega_{ZOR}^{open} = \omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \quad rad/s \tag{3.7}$$

i.e. For the open-ended boundary condition of the zeroth-order resonator, the frequency depends on the shunt LC resonant tank [20]. Because the CRLH TLs have periodic boundary conditions, the Bloch-Floquet theorem can be applied and its dispersion characteristics can be determined [19] by,

$$\beta(\omega) = \cos^{-1}\left[1 - \frac{1}{2}\left(\frac{\omega^2}{\omega_R^2} + \frac{\omega_L^2}{\omega^2} - \frac{\omega_L^2}{\omega_{se}^2} - \frac{\omega_L^2}{\omega_{sh}^2}\right)\right] \tag{3.8}$$

and ω_L and ω_R are given by

$$\omega_L = \frac{1}{\sqrt{L_L C_L}} \quad rad/s \tag{3.9}$$

$$\omega_R = \frac{1}{\sqrt{L_R C_R}} \quad rad/s \tag{3.10}$$

and the resonance of the CRLH TL for resonant modes n can be obtained by the following [17] equation (3.11).

$$\beta_n p = \frac{n\pi p}{l} = \frac{n\pi}{N}, \qquad n = (0, \pm 1, \pm 2, \ldots, \pm(N-1)) \tag{3.11}$$

where N, n and l are the number of unit cells, mode number and total physical length of the resonator, respectively.

Consider the open-ended TL, where Z_L=∞, the input impedance (Z_{in}) seen from one end of the resonator toward the other end is given by

$$\begin{aligned} Z_{in}^{open} &= -jZ_c \cot(\beta l) \overset{\beta \to 0}{\approx} -jZ_c \frac{1}{\beta l} \\ &= -j\sqrt{\frac{Z'_{series}}{Y'_{shunt}}}\left(\frac{1}{-j\sqrt{Z'_{series} Y'_{shunt}}}\right)\frac{1}{l} = \frac{1}{Y'_{shunt} l} \\ &= \frac{1}{Y'_{shunt}(N\Delta z)} \end{aligned} \tag{3.12}$$

where Y'_{shunt} is the admittance of the CRLH unit cell. From (3.12), the input impedance of the open-ended resonator is equal to 1/N times $1/Y'_{shunt}$ of the unit cell. The equivalent L, C, G values are equal to L_L/N, NC_R, and 1/NG, respectively [39]

3.3 Zeroth Order Resonator (ZOR)

An antenna is said to be resonant if its input impedance is entirely real, i.e. $Z_{in} = R + j0$. In this case the voltage and current are in phase at the antenna's terminals. This property makes the impedance matching of an antenna to an transmission line and receiver easier [2], as the imaginary part of the impedance does not need turned out.

In addition, when viewing the frequency plot for an antenna, there is often a large decrease in the magnitude of reflection coefficient around the resonant frequency, indicating that power is radiated well around this frequency.

When n=0 in (3.11), the wavelength becomes infinite and the resonant frequency of the zeroth-order mode becomes independent of the size of the antenna. When ZOR antenna operates at resonant frequency that has zero propagation constant ($\beta = 0, \omega \neq 0$), in other words, it supports infinite wavelength at a finite nonzero frequency. As a result, the ZOR antenna is independent of the physical length, so that the size of the structure could be arbitrary small and more compact than the conventional half-wavelength antennas.

3.4 Application of MTM TL

Metamaterial transmission lines have been applied to many fields successfully. They may extend the performance of conventional microwave components due their unique dispersion characteristics. When the TL is used as a Zeroth Order Resonator (ZOR), it allows a constant amplitude and phase resonance across the entire resonator. On the other aspect, they may reduce the dimensions of some conventional microwave components greatly. The applications of MTM TL are

- Leaky-Wave Antenna
- Balun
- Diplexer
- Directional couplers
- Power combiner/splitter

Furthermore, metamaterials can be used on the ground plane interconnecting adjacent antennas in order to control the cross-talk of signals, thus reducing mutual coupling.

3.5 Conclusion

Thus CRLH TL is able to achieve left-handed (LH) metamaterial properties by the way of the circuit parameters. In addition, due to the zero propagation constant inherent in the LH metamaterial properties, the resonator has an infinite wavelength and its resonant frequency is independent of the size of the resonator. Therefore, the zero propagation constant properties of resonant antennas enable them to be more compact than conventional half-wavelength antennas. Thus, the CRLH TL extended the performance of conventional microwave components due their unique dispersion characteristics.

Chapter 4

ZOR Antenna Design Based on CRLH-TL

This chapter Presents the design and analysis of Asymmetric Coplanar Waveguide (ACPW) Zeroth-Order Resonant (ZOR) Based on Composite Right Left Handed Transmission Line (CRLH TL). There have been a number of studies that have investigated how to enhance the bandwidth of ZOR antennas. In this chapter, we proposed a new type of single-layer ZOR antenna that is based on asymmetric coplanar waveguide (ACPW) for a further bandwidth extension. This ZOR antenna extends the bandwidth up to 9.24% while keeping high radiation efficiency.

The bandwidth of ZOR antenna depends on a Q-factor of the shunt resonator,i.e., the shunt inductance and capacitance of the CRLH-TL [40]. Hence, by modulating the shunt reactance can increase the bandwidth of ZOR antenna.Coplanar waveguides are uniplanar transmission line structures where the ground plane & and signal trace are placed on the same side of substrate. The proposed ZOR antenna keeps the design freedom of CPW and also utilizes the ACPW to evade the design challenge about the large shunt inductance at CPW. As an advantage of the proposed method, it is easy to manufacture a low-profile omnidirectional ACPW ZOR antenna with good radiation efficiency, good bandwidth, and without any lumped components to achieve good antenna gain.

As mention earlier in section 1.6, since the Zeroth Order Resonator (ZOR) antenna suffers from low bandwidth around the resonating frequency, the main objective of present research work is to propose efficient technique for extending bandwidth and increasing gain while maintaining high efficiency.

4.1 Bandwidth Extension Technique

Considering that the open ended resonator is only dependent on Y'_{shunt} of the unit cell, the average electric energy stored in the shunt capacitor, C_R, is given by

$$W_e = \frac{1}{4}|V^2|NC_R \tag{4.1}$$

and the average magnetic energy stored in the shunt inductor, L_L, is

$$W_m = \frac{1}{4}|I_L|^2\frac{L_L}{N} = \frac{1}{4}|V|^2\frac{N}{\omega^2 L_L} \tag{4.2}$$

where I_L is the current through the inductor.

Because resonance occurs when W_m is equal to W_e, the quality factor can be calculated as follows:

$$\begin{aligned} Q &= \omega\frac{average energy stored}{energy loss/second} \\ &= \omega_{sh}\frac{2W_m}{P_{loss}} = \frac{1/NG}{\omega_{sh}(L_L/N)} = \frac{1/G}{\omega_{sh}L_L} \\ &= \omega_{sh}(1/NG).NC_R = \omega_{sh}(1/G)C_R \\ &= \frac{1}{G}\sqrt{\frac{C_R}{L_L}} \end{aligned} \tag{4.3}$$

Therefore, in the open ended case , the fractional bandwidth of the resonator is given by

$$BW = (Q_0^{open}) = G \times \sqrt{\frac{L_L}{C_R}} \tag{4.4}$$

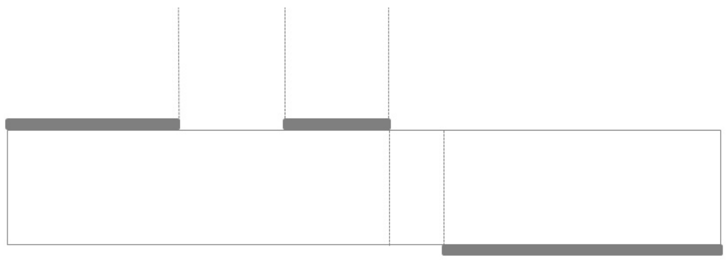
Although this equation does not consider the impedance matching at the input terminals, it provides an intuitive concept by means of which the bandwidth can be efficiently increased [13–16].

According to (4.4), the bandwidth of the open-ended ZOR antenna depends on the loss G and shunt element of CRLH-TL equivalent circuit model in the shunt tank. Therefore, we can increase the bandwidth by introducing a high shunt inductance and a small shunt capacitance using our proposed ACPW structure.

4.2 Proposed Antenna Realization

Generally, ZOR antennas are known to have a narrow bandwidth problem compared to conventional resonant antennas. This is because the Q-factor of a ZOR antenna is only related to C_R and L_L. For example, in a microstrip structure,C_R and L_L are realized by the shorting pin (via) and parallel plate between the top patch and bottom ground. Since L_L in a microstrip line (MSL) depends on the length of the via, the microstrip structure limits the value of L_L. In addition, since the thickness and size of the substrate determine the capacitance of the parallel plate, the MSL has a large C_R. The narrow bandwidth is originated from the small L_L and large C_R. Therefore, the ZOR antenna in microstrip technology has a narrow bandwidth due to the structural problem. In order to extend the bandwidth of the microstrip structure, a thick substrate with low permittivity is generally utilized. However, this causes fabrication difficulties and reduces the design freedom. All these can be overcome by our proposed topology. In this design topology, we focus

(a) Top view



(b) Side view

Figure 4.1: Configuration of the proposed CRLH-TL unit cell design.(a) Top view. (b) Side view.

on antenna with large L_L and small C_R, which result in improved bandwidth without degrading the efficiency, due to the shunt conductance (G). Moreover, We suggest a structure which can be easily fabricated and offers more design freedom.

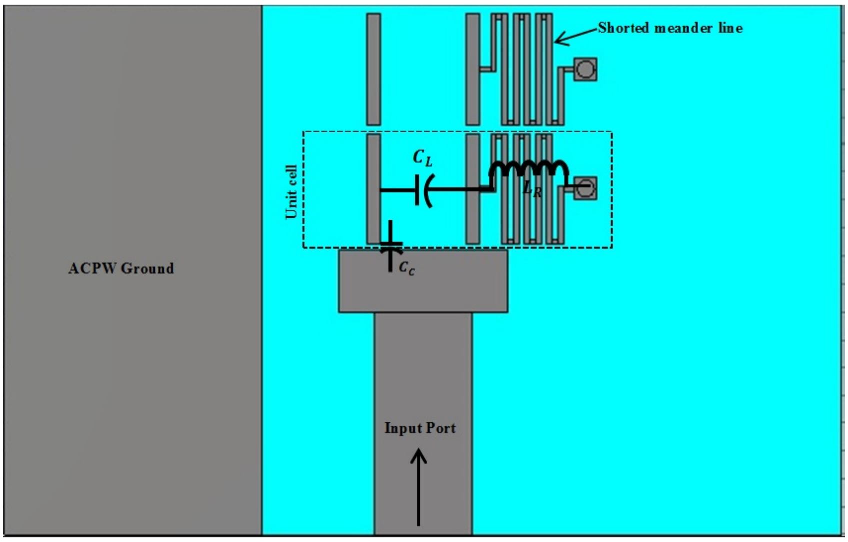


Figure 4.2: Parameter extraction of unit cell of the proposed ACPW ZOR antenna based on CRLH TL.

In the above Fig.4.1 (a) shows the top view of a proposed CRLH TL single unit cell and, (b) shows the side view of the antenna.

In Fig.4.2 parameter extraction of unit cell of the proposed ACPW ZOR antenna based on CRLH TL is shown, and proposed ACPW ZOR antenna with physical dimensions shown in Fig.4.4.

In addition, we proposed the bandwidth enhancement ACPW ZOR antenna by increasing the $L_L$and decreasing C_R according to (4.4).Fig.4.4 illustrates the proposed ACPW-based open-ended ZOR antenna that cascades two unit cells periodically. We put one of the ground planes of CPW to the bottom layer of the substrate to form the ACPW structure and maintain the unit cell printed on the top layer.

To increase the bandwidth, by applying (4.4), first we increase the L_L of the proposed unit cell. Since it is difficult to fulfill compact meander lines on the conventional CPW, we take advantage of one side of ACPW to realize large L_L such that it is an MSL-like structure at this side, while the ground plane is located at the bottom. Therefore, we can design compact meander lines in the ACPW while maintaining the feature of CPW simultaneously. In addition, the gap between the two strips on top layer provides the series LH capacitance C_L and the magnetic flux produced by the current flow along the meander line provides the parasitic series RH inductance L_R. Each unit cell is shorted to the bottom ground plane through via, provides shunt LH inductance L_L and the shunt LH capacitance C_R will come from gap between top and bottom layer. Distinct from MSL, which has large due to the fixed thickness of substrate, maintaining a CPW-like structure on the other side provides design freedom such that the small can be controlled by the dimension of the gap g. Moreover, by adjusting the area g_4 as shown in Fig.4.3 of

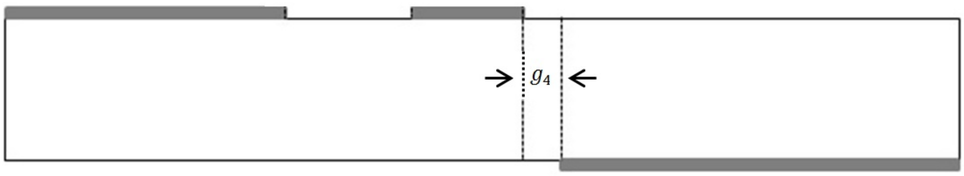
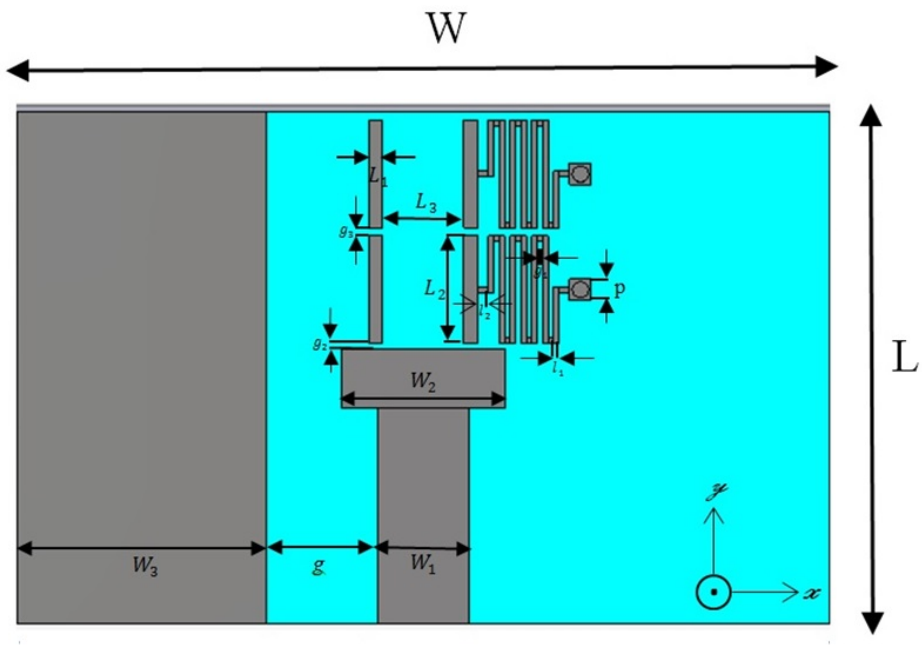
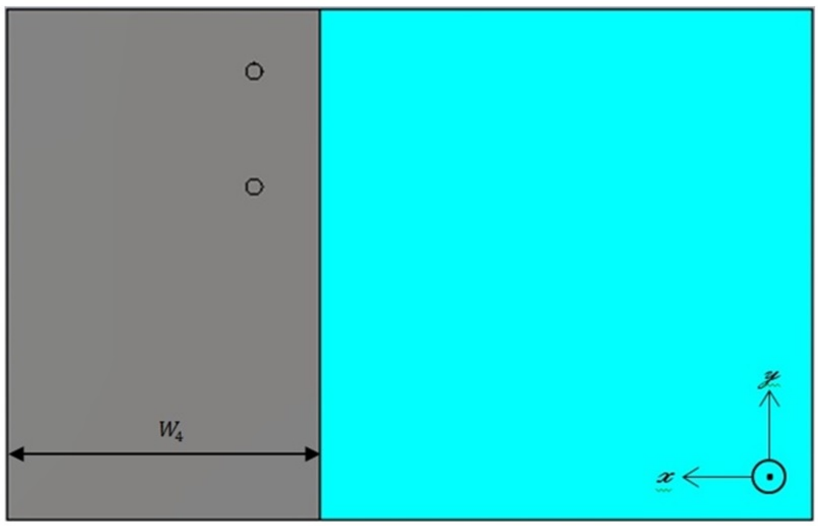


Figure 4.3: ACPW ZOR antenna side view indication g_4, gap between signal line and bottom ground plane

the signal line and the bottom ground plane appropriately, small C_R is obtained and also easy for impedance matching.



(a) Top view



(b) Bottom view

Figure 4.4: Geometric of the proposed ACPW ZOR antenna based on CRLH-TL design.(a) Top view. (b) Bottom view.

4.3 Experimental Results

The proposed ZOR antenna is fabricated on a single -layer substrate of FR4 (lossy) with a dielectric constant of 4.3 and thickness of 1.6 mm, and $\tan\delta = 0.025$ is show in Fig.4.7. The physical dimensions of the proposed antenna shown in Fig.4.4 are (unit: millimeter): $W_1 = 3.4$, $W_2 = 6$, $L_1 = 0.5$, $L_2 = 4$, $L_3 = 3$, $l_1 = 0.2, l_2 = 0.4$, $g_1 = g_2 = 0.2$, $g_3 = 0.3$. The proposed antenna is designed to have zeroth-order mode at 4.57 GHz. The electrical size of the unit cell of the ZOR antenna is $0.125\lambda_0 \times 0.064\lambda_0 \times 0.024\lambda_0$ at 4.57 GHz. The overall area of the radiating aperture is approximately $0.457\lambda_0 \times 0.289\lambda_0 \times 0.024\lambda_0$ ($30mm \times 19mm \times 1.6mm$). Fig.4.5 shows the simulated reflection coefficients where the resonant frequency of Zeroth-order mode is at 4.57 GHz. Moreover, the measured 10 dB bandwidth, radiation efficiency and omnidirectional peak gain (dBi) are 9.24%, 75.36% and 1.93 respectively.

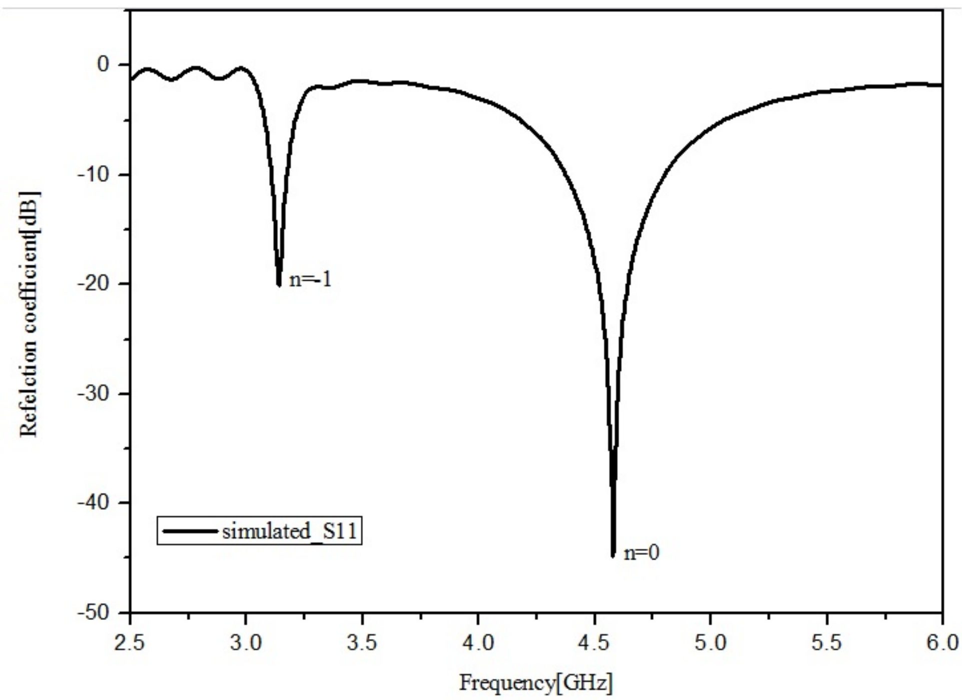
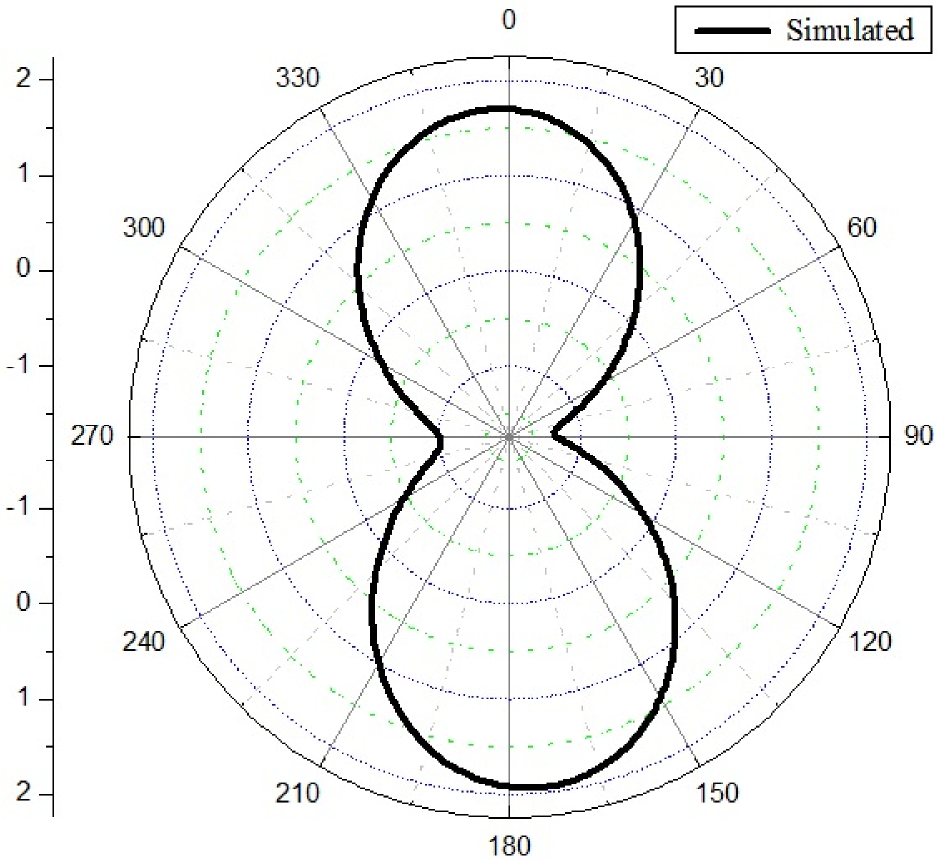
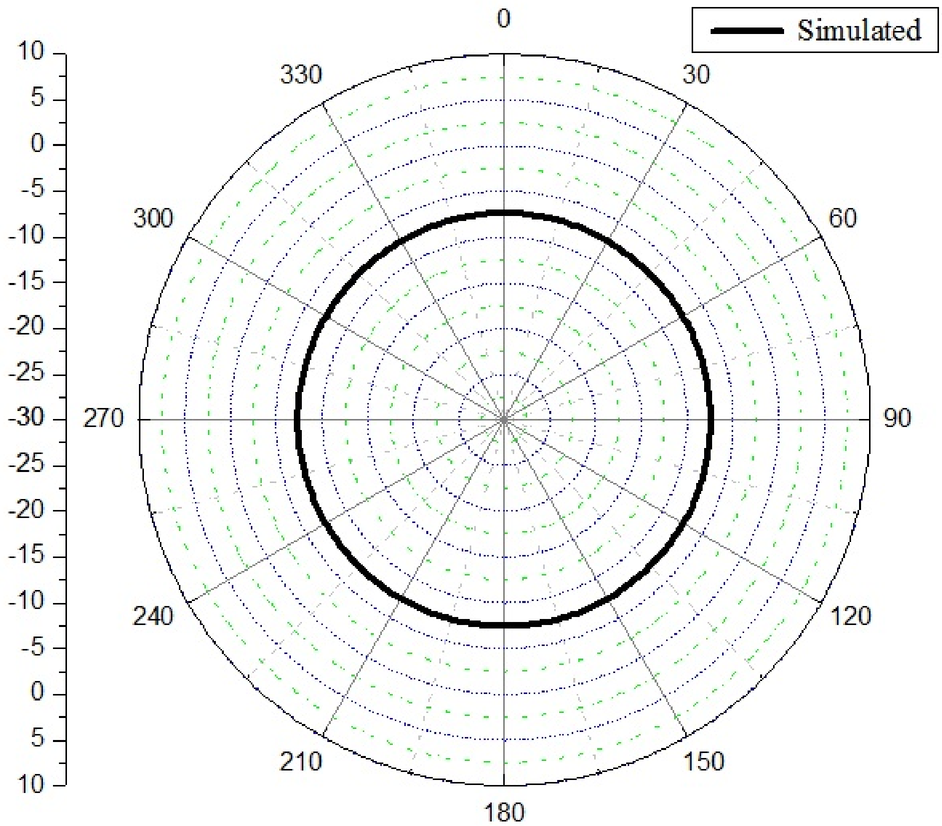


Figure 4.5: Simulated reflection coefficient for $g_2 = 0.2mm$, $g_4 = 1.6636mm\ and\ G = 4.07mm$, and the Zeroth-order resonance frequency is 4.57 GHz.



(a)



(b)

Figure 4.6: Simulated radiation patterns of the symmetric antenna at 4.57 GHz: (a) y-z plane (E-plane), (b) x-z plane (H-plane)

From Fig.4.5,for $g_2 = 0.2mm,\ g_4 = 1.6636mm\ and\ G = 4.07mm$, and the Zeroth-order resonance frequency is 4.57 GHz the frequencies f_1 and f_2 are given by 4.376 GHz and 4.8 GHz respectively. Then, the fractional bandwidth from (1.10) can be calculated as,

$$\begin{aligned} f_c &= \frac{f_1 + f_2}{2} = \frac{4.376 + 4.8}{2} = 4.588\ GHz \\ BW(\%) &= \frac{f_2 - f_1}{f_c} \times 100 \\ &= \frac{4.8 - 4.376}{4.588} \times 100 \\ BW(\%) &= 9.24 \end{aligned}$$

Hence, with the bandwidth extension technique of ZOR, the proposed ZOR antenna's bandwidth has been extended up to 9.24%.

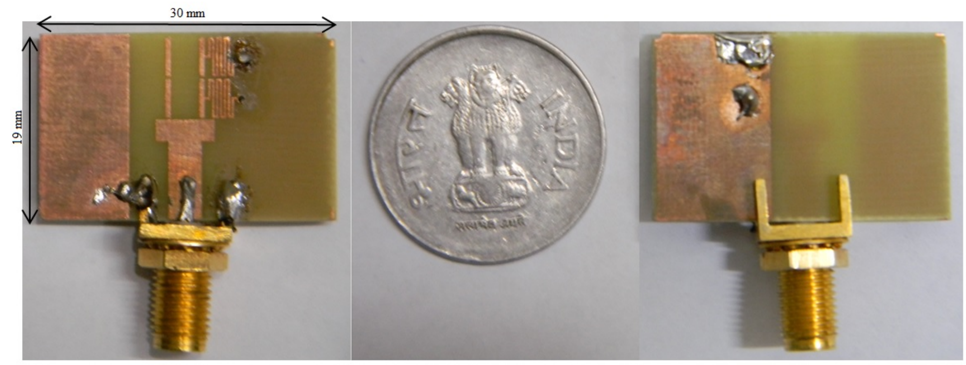


Figure 4.7: Top and bottom view of the fabricated prototype of ACPW ZOR antenna.

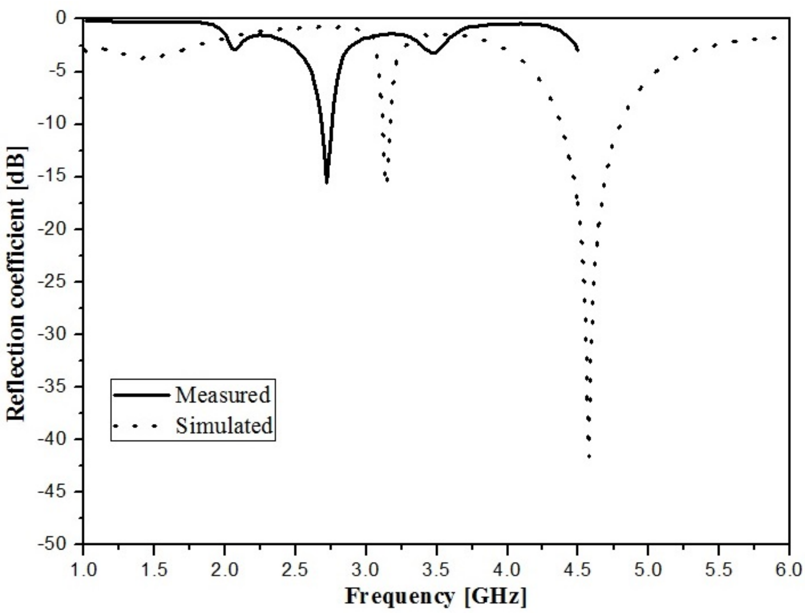


Figure 4.8: Simulated and measured reflection coefficients of the Proposed ACPW ZOR antenna

Table 4.1: Summary of the proposed ACPW ZOR antenna at two resonant frequencies.

Frequency (GHz)	3.14	4.57
Bandwidth (%)	2.12	9.24
Directivity (dBi)	1.973	3.16
Gain (dBi)	-6.58	1.93
Efficiency (%)	14	75.36

Table 4.2: Proposed ACPW ZOR Antenna summary and comparison with reference antennas.

	This Work	[13]	[14]	[16]	[19]
Frequency(GHz)	4.57	1.77	1.73	2.03	3.38
Unit Size(λ_0)	$0.125\times 0.064\times 0.024$	$0.09\times0.077\times 0.036$	$0.1\times0.1\times 0.015$	$0.053\times0.097\times 0.011$	$0.16\times0.08\times 0.017$
Bandwidth(%)	9.24	6.8	8	6.8	~ 0.1
Gain(dBi)	1.93	0.95	1	1.35	0.87
Efficiency(%)	75.36	54	-	62	70
Layer	Single	Multi	Multi	Single	Single

4.4 Parametric study

From (3.7) and (4.4), it is clearly indicating that the resonating frequency and extending bandwidth of ZOR antenna completely depends on shunt LC resonant tank. Thus, the resonance frequency and realized gain variations for different circuit parameter values have been brought out here.

Fig.4.9 and Fig.4.9 shows the resonance frequency and realized gain variations for the different values of g, gap between front ground plane and radiating patch. In Fig.4.9, it clearly demonstrates that the resonating frequency remains constant as the gap g is increased. Fig.4.10 shows the relationship between realized gain and the g value.

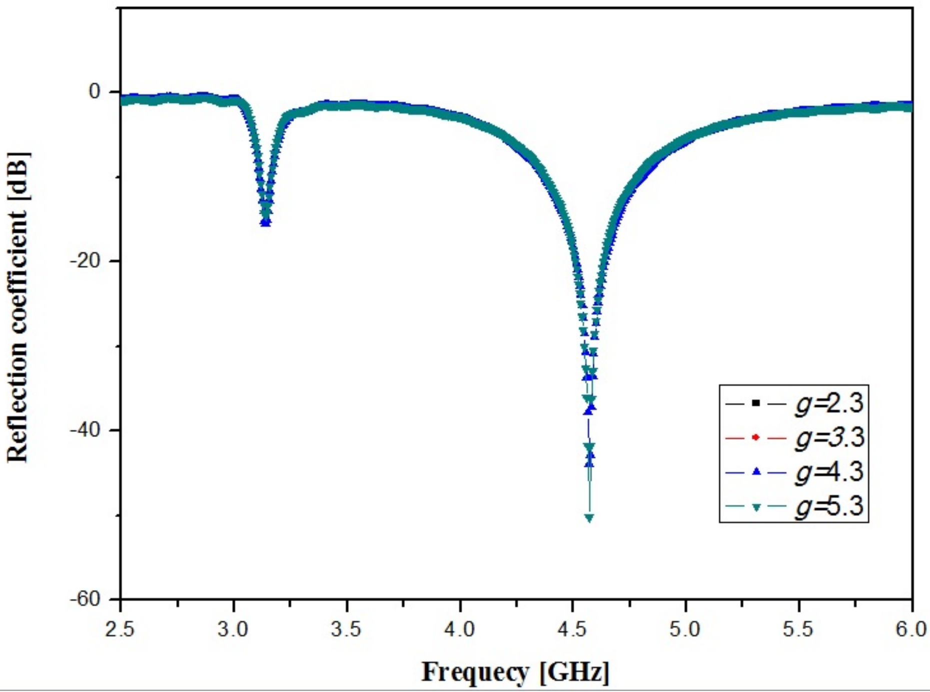


Figure 4.9: Reflection coefficient of ZOR antenna at different values of g.

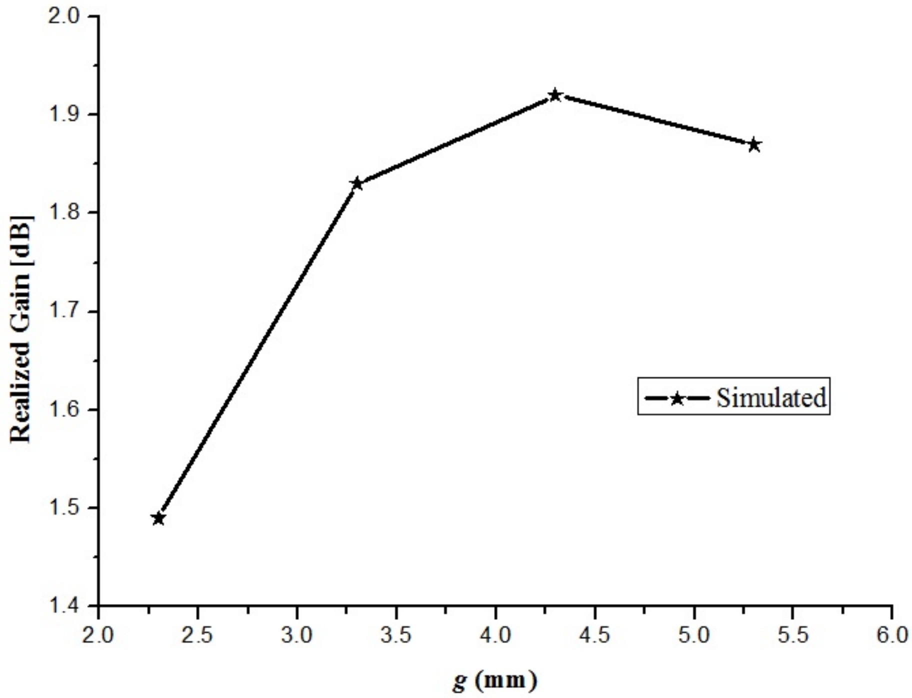


Figure 4.10: Comparison of realized gain at different values of g.

Fig.4.11 and Fig.4.12 shows the resonance frequency and realized gain variations for the different values of g_2, gap between radiating patch and unit cell .i.e gap offered by coupling capacitance C_C. In Fig.4.11, it clearly demonstrates that the resonating frequency has little variations for changes in g_2. Fig.4.12 shows the relationship between realized gain and the value g_2, and here it demonstrates that gain values is depends on the value C_C and it can be controlled by varying C_C.

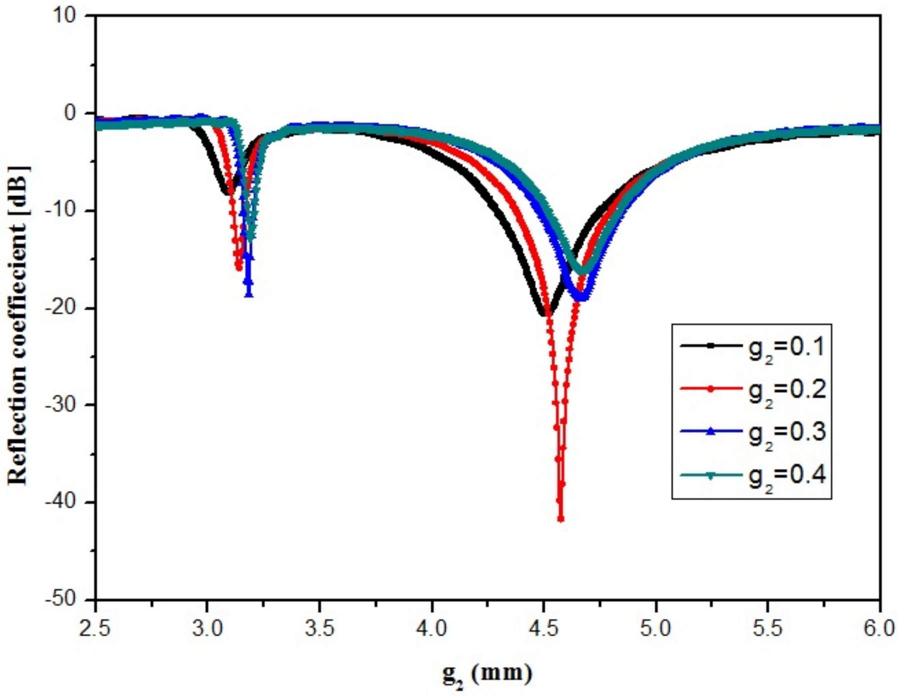


Figure 4.11: Reflection coefficient of ZOR antenna at different values of g_2.

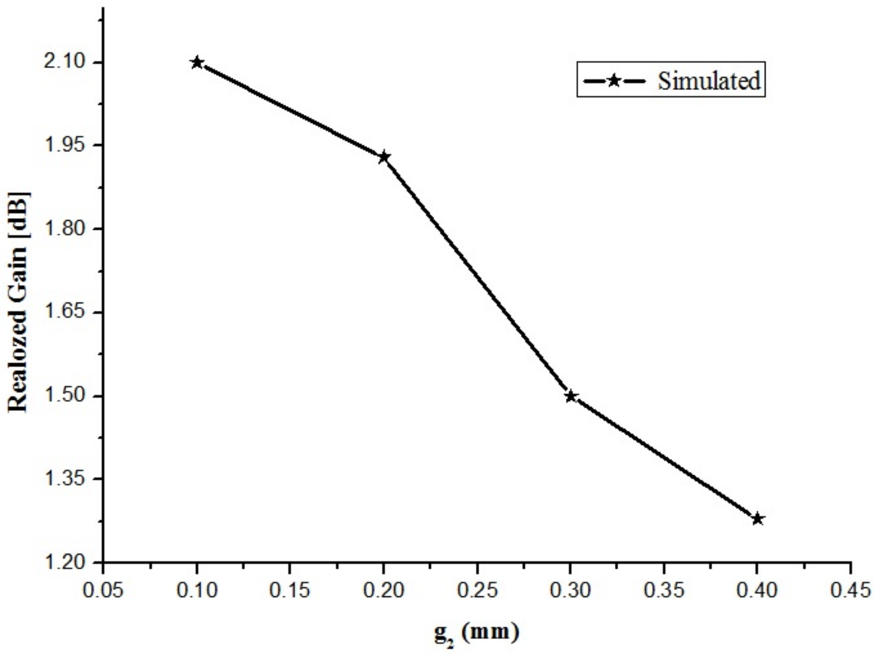


Figure 4.12: Comparison of realized gain at different values of g_2.

Fig.4.13 and Fig.4.14 shows the resonance frequency and gain variations for the different values of g_4 gap between signal line and bottom ground plane, refer Fig.4.3. As mentioned earlier and from (3.7) and (4.4), it is clearly indicating that in Fig.4.13 the resonating frequency and extending bandwidth of ZOR antenna completely depends on shunt LC resonant tank. Fig.4.13 clearly shows that the resonating frequency variation as the gap g_4 is varied. Fig.4.14 shows the relationship between gain and the value g_4.

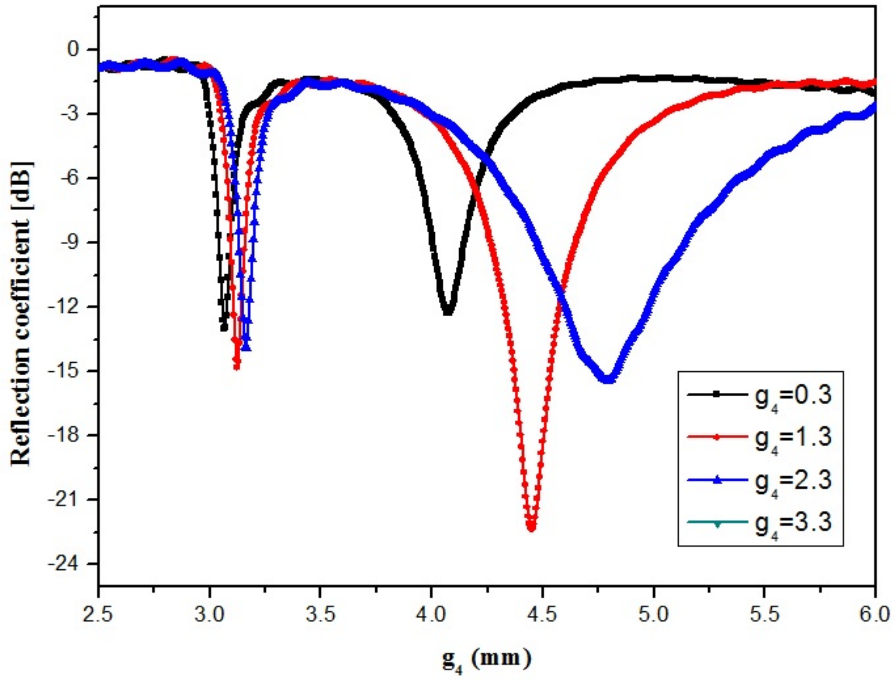


Figure 4.13: Reflection coefficient of ZOR antenna at different values of g_4.

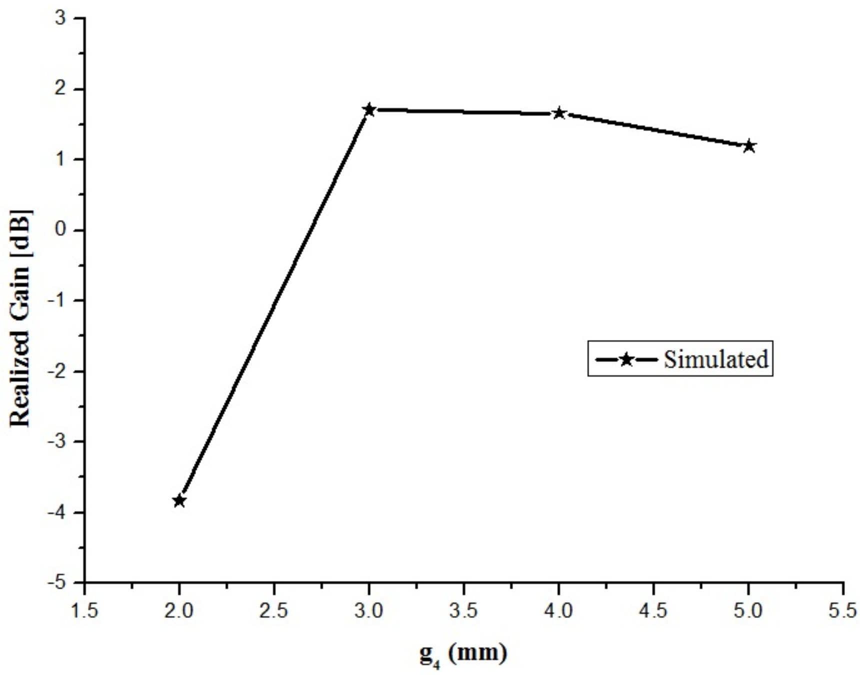


Figure 4.14: Comparison of realized gain at different values of g_4.

4.5 Conclusion

In this study, we demonstrated the extended bandwidth of the proposed ACPW ZOR antenna with compact size and low profile,and fabricated. The bandwidth of ZOR antenna has been extended by realizing a high shunt inductance and small shunt capacitance based on the proposed design of a single-layer ACPW structure. In addition, the ACPW ZOR antenna based on CRLH TL extends the bandwidth up to 9.24%, radiation efficiency up to 75.36% and peak gain of 1.93 dBi at the operating frequency of 4.57 GHz. Therefore, due to all these features, the proposed ACPW ZOR antenna is suitable for use in Wi-Fi devices and cordless telephones.

Chapter 5

Conclusion and Future Work

In this chapter, the conclusion of the whole thesis is presented and future research problems are outlined for further investigation in the same or related topics.

5.1 Conclusion

In this thesis, about "*Metamaterial*" and its terminology, Left Handed metamaterial, Right Handed material and Composite metamaterial have been presented. And also brief explanation about materials with negative permeability ($\mu < 0$), and negative permittivity ($\epsilon < 0$), and also material that exhibit both properties ($\mu < 0$) and ($\epsilon < 0$) simultaneously over the common range of frequencies called *Negative Index of Refraction* or *Negative Refractive Index* is presented.

Basic understanding of electromagnetic wave response to the material with negative refractive index, and how the wave propagation inside the NRI material and conventional material has been explained diagrammatically. And also in chapter 2, salient features of negative-refractive-index metamaterials, methods to realize Left Handed (LH) Media or Negative Refractive Index (NRI) are, (a) Split Ring Resonator, (b) Transmission Line methods have been presented.

Powerful analysis tool for the understanding and realization of NRI is Transmission Line theory in terms of the circuit parameters. By including the Right-Handed (RH) effect into a purely Left-Handed (LH) circuit, it represents the most general form of a practical metamaterial TL structure, called Composite Right Left Handed Transmission Line (CRLH TL). This solution has been widely recognized and adopted as a powerful analysis tool for the understanding and design of metamaterial devices. In order to realize

CRLH TL circuit different type of possible lumped microwave components have been presented in chapter 3.

One of the novel applications of metamaterial is the Zeroth Order Resonant (ZOR) antenna, which is based on Composite Right Left Handed (CRLH) Transmission Lines (TLs) periodic structures. Due to the unique electromagnetic properties of metamaterial, such as anti-parallel phase and group velocities and zero propagation constant ZOR antenna supports infinite wavelength at a finite nonzero frequency. As a result, the ZOR antenna is independent of the physical length, so that the size of the structure could be arbitrary small and more compact than the conventional half-wavelength antennas.

A novel low-profile ZOR antenna based on CRLH TL is presented in chapter 4. However, these antennas suffer from the narrow bandwidth such that it is hard to be applied to wireless communication systems. There have been a number of studies that have investigated how to enhance the bandwidth of ZOR antennas. In this thesis investigation made on *" Extending Bandwidth of ZOR antennas"* has been presented to extend the bandwidth of proposed ACPW ZOR antenna based on CRLH TL. We develop our proposed ACPW ZOR antenna on single layer for a further bandwidth extension. The performance of proposed antenna is listed in Table 4.1and the comparison of proposed ACPW ZOR antenna with reference antennas is listed in Table 4.2. Thus, this ZOR antenna extends the bandwidth up to 9.24% while keeping high radiation efficiency at 75.36% with omnidirectional peak gain of 2.3 dBi.

5.2 Future work

In modern engineering applications, metamaterial to become more commonplace stable and robust designs are needed. The research work presented in the thesis can be further extended in following ways.

- As day to day in modern life, the dependent on portable devices such as laptops, mobile phones increasing rapidly. So,the functions and components to be embedded into portable devices rapidly increasing. And the space left for the engineers to integrate all the necessary components becomes smaller. Primarily, the further investigation is designing further more compact size antennas with high efficiency to achieve all the requirements of handheld wireless devices in modern day to day life.
- In addition, to meet the demands for the multi-function of devices, such as mobile phone, bluetooth transmission and AM/FM radio multiple antennas will be integrated together in a single module. To simplify the multi-functioning of de-

vices without much design complexity in design multi-band antennas are required in order to increase the overall system capacity.

- Future work along these lines would include further explorations into the use of metamaterials for the development of complete MIMO front-end radio systems. Possible areas where metamaterials could be used to improve system performance include filters, diplexers, mixers, power amplifiers, phase shifters and further antenna optimization in terms of size and bandwidth.

- Another extension of the existing work is to construct a devices in integrated circuit form in a low-cost CMOS process, which can also be integrated with MEMS devices in order to realize active metamaterials.

Finally, Veselago's conceptual exploration of negative refractive index in the late 1960s have been received today's world substantial attention in the scientific and engineering communities. Experimental verification of Left Handed Media or Negative Refractive Index did not occur until three decades. It took almost over thirty-five year to verify veselago's principle idea experimentally using electromagnetic artificial dielectrics. Thus metamaterial antennas open a way to overcome the restrictive efficiency-bandwidth limitations for small antennas. Hence metamaterial represents an exciting emerging research area that promises to bring about important technological & scientific advancements in diverse areas such as telecommunications, radar & defence, microelectronics, medical imaging . . . etc.

There is a great hope that metamaterial may be able to provide additional degrees of freedom and better performance for electromagnetic communication and their effective use in various microwave and antenna applications systems. We are looking forward to observing more engineering applications of these antennas in the near future.

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